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Advanced Approaches to Digital Design for Rare Earth-Free Traction Motors

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14th May 2024

Topics

- Electrification Challenges
- Introduction to Digital Design Process
- Traction Induction Machine Case
- Traction Synchronous Reluctance Machine Case
- Traction Synchronous Wound Field Machine Case

Electrification Challenges

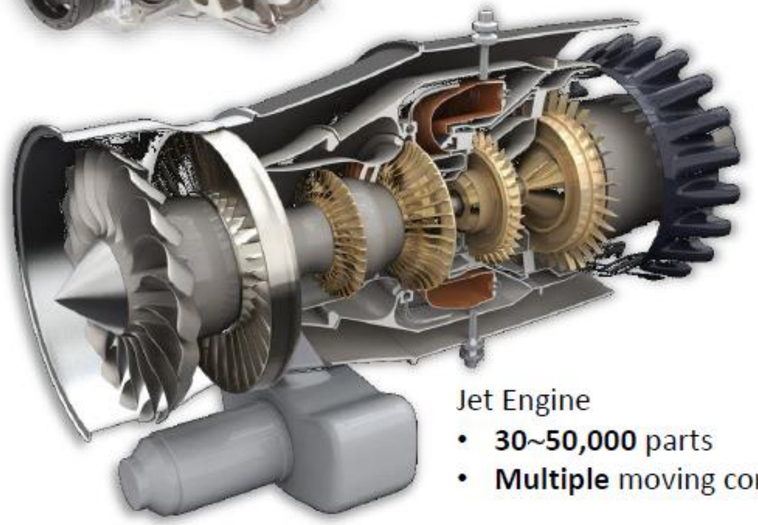
Electrification Challenges

- There is a strong imperative to decrease the volume and cost of active materials in propulsion motor technologies beyond their current state-of-the-art.
- Potential solutions encompass heightened motor speeds and increased pole numbers and/or alternative types such as asynchronous reluctance, electrically excited, and induction machines with reduced reliance on rare-earth materials.
- Due to significantly varied usage and performance requirements across e-mobility applications, adopting a common standard of motor design is unlikely to yield optimal results in terms of overall system energy efficiency and cost-effectiveness.
- Design software must evolve to meet the demands of these new technological developments and provide a user-friendly experience, even for non-specialist users.

Electrification Challenges : Digital Design

- Interactions between **different physical domains** lead to **conflicting performance metrics**
- Increasing need for **multiphysics design and analysis** to meet **multicriteria requirements**

Automobile Combustion Engine
- **6~7,000** parts
- **Multiple** moving components



VS.

Jet Engine
- **30~50,000** parts
- **Multiple** moving components

Multiphysics problem — Multicriteria requirements

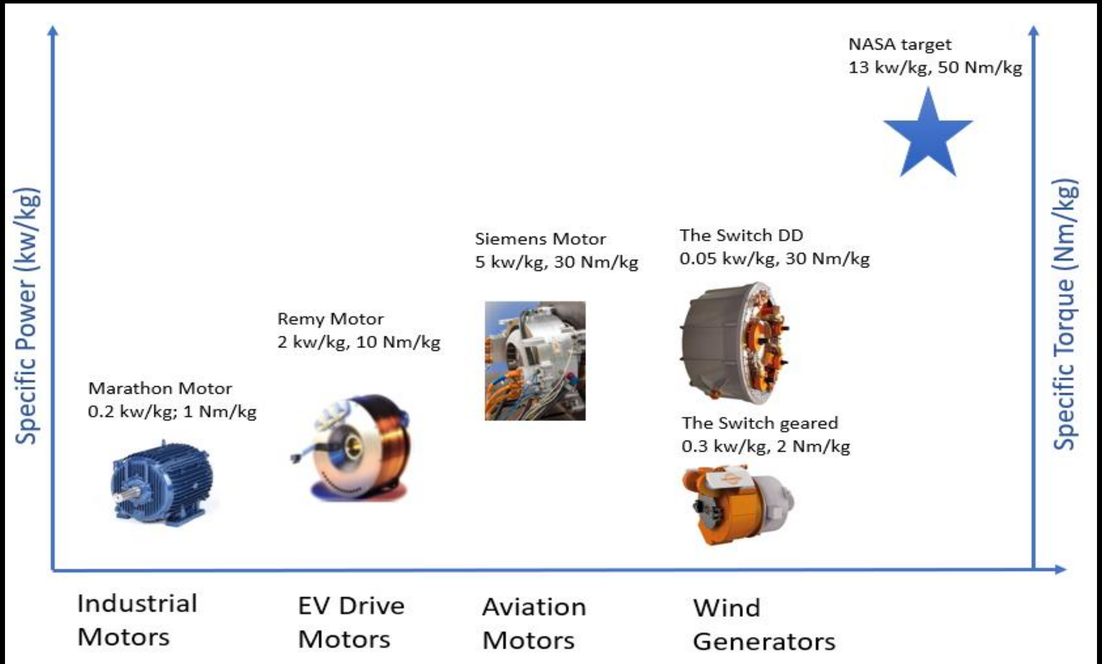
Electric motor
- Less than **100** parts
- **One** moving component

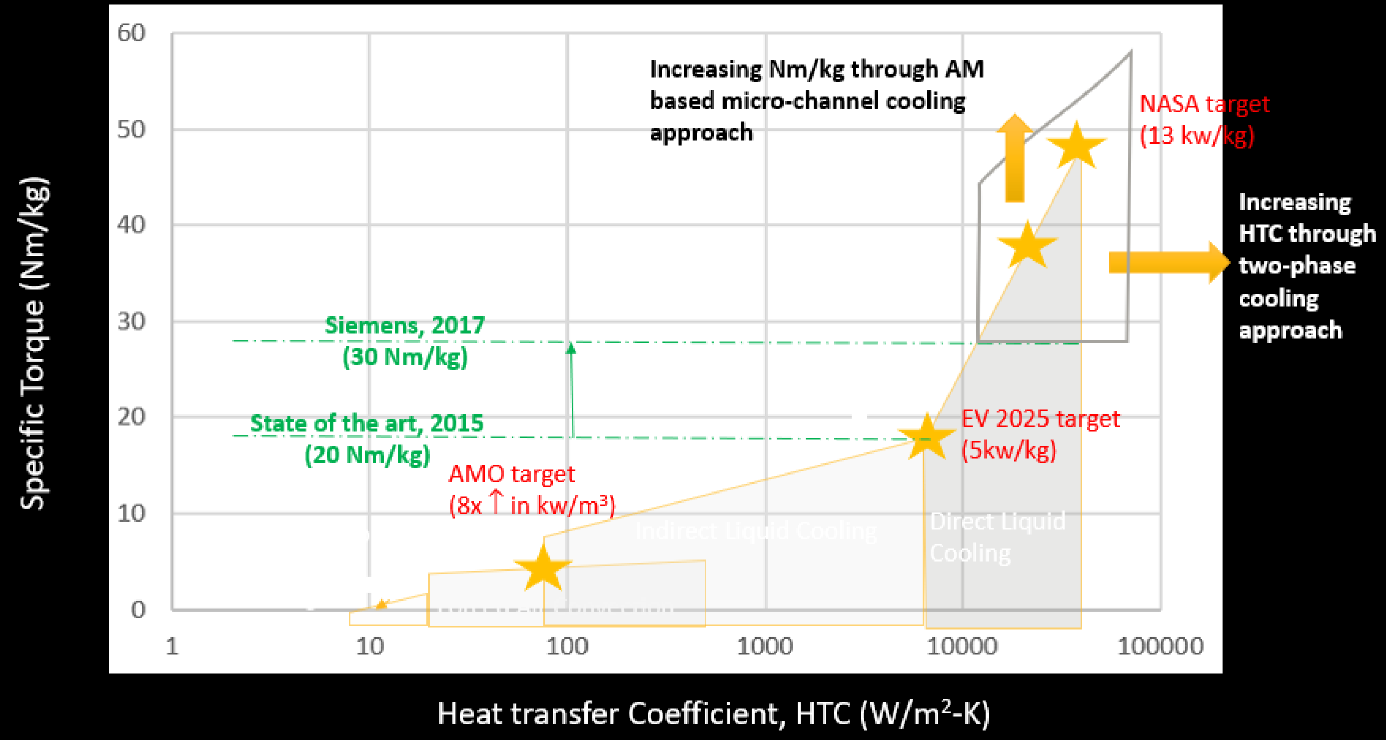
- **Electromagnetic:** Torque, efficiency
- **Electrical:** High voltage/current
- **Thermal:** Cooling, peak/cont. ratings
- **Mechanical:** Robustness at high speed, NVH

- **High Efficiency (%)**
- **High torque/power density (kW/kg)**
- **Reducing cost ($/kW)**
- **Shorter development cycles**

Road to High-Power Density Electrical Machines

- Cooling system – one of the key elements to increase performance in electrical machines





Source: Z. Rahman, ARPA-E, 2019

Traction Motors For EVs*

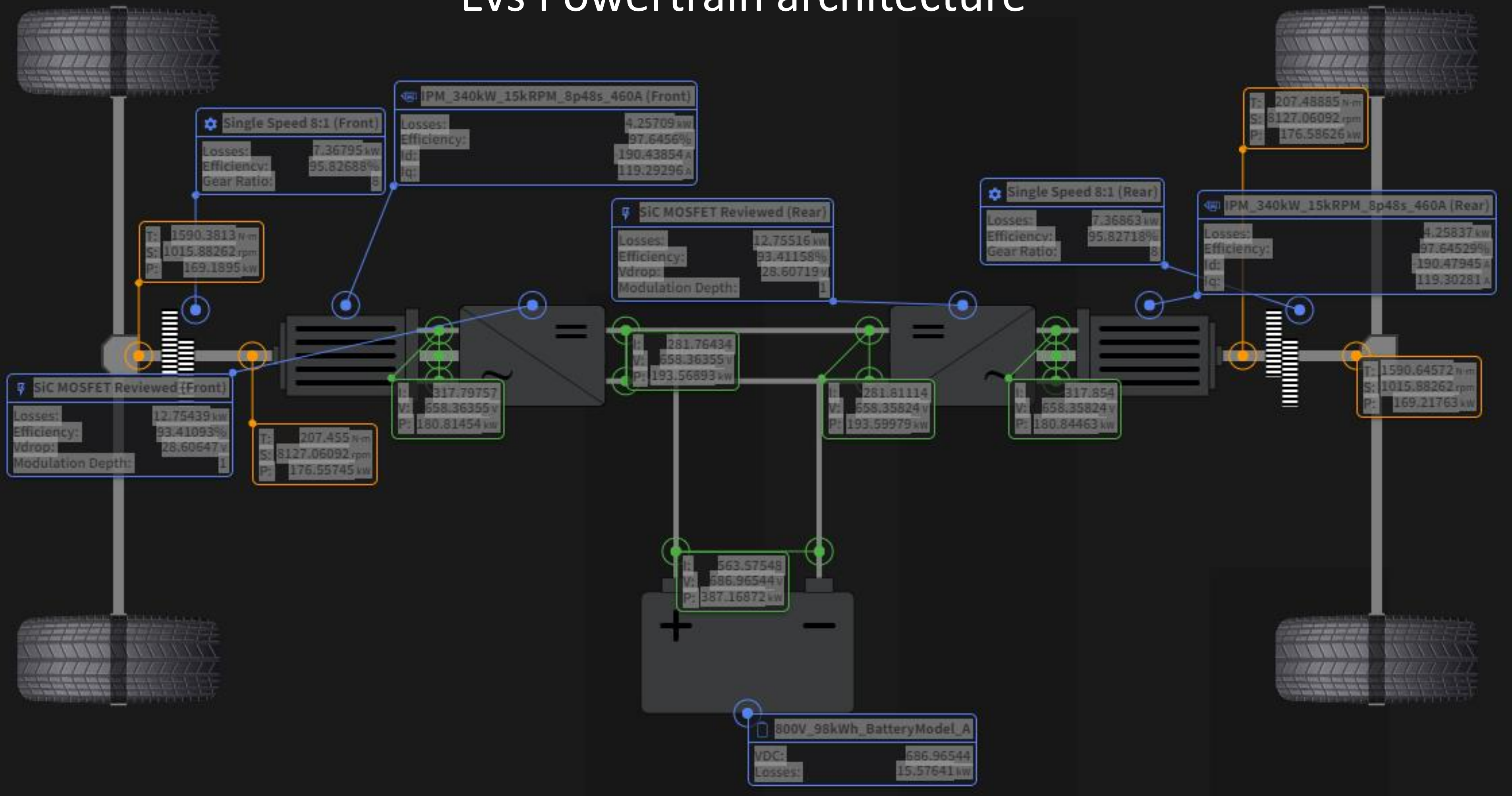
- Most solutions based on permanent magnet motors configuration
- PMSM = PM Synchronous Motor
- PMASynRel = PM Assisted Synchronous Reluctance Motor
- IM = Induction Motor
- SynRel = Synchronous Reluctance Motor
- WRSM = Wound Rotor Synchronous Motor

Vehicle Model	**Motor type Front / Rear**
Audi e-tron 55	IM / IM
BMW i3S 33/42	- / PMASynRel
FIAT 500e	PMSM / -
Hyundai e-Kona 39	PMSM / -
Hyundai e-Kona 64	PMSM / -
Jaguar I-Pace	PMSM / PMSM
KIA e-Niro 4	PMSM / -
KIA Soul EV 39	PMSM / -
KIA Soul EV 64	PMSM / -
Mercedes-Benz EQC	IM / IM
MINI Cooper SE	PMSM / -
Opel Mokka-e	PMSM / -
Opel Corsa-e	PMSM / -
Porsche Taycan 4S	PMSM / PMSM
Porsche Taycan Turbo	PMSM / PMSM
Renault Twingo EL	WRSM
Renault Zoe R135	
ŠKODA CITIGOe	PMSM / -
Tesla Model 3	IM / PMASynRel
Tesla Model X	PMASynRel / IM
Tesla Model Y	IM / PMASynRel
Tesla Model S	PMASynRel / IM
Volkswagen e-Golf	PMSM / -
Volkswagen e-up!	PMSM / -
Volkswagen ID.3	- / PMSM
Volkswagen ID.4	- / PMSM
Volvo XC40	PMSM / PMSM

* *EVSpecifications, Electric Car News, EV Comparisons* https://www.evspecifications.com

Traction Motors For EVs*

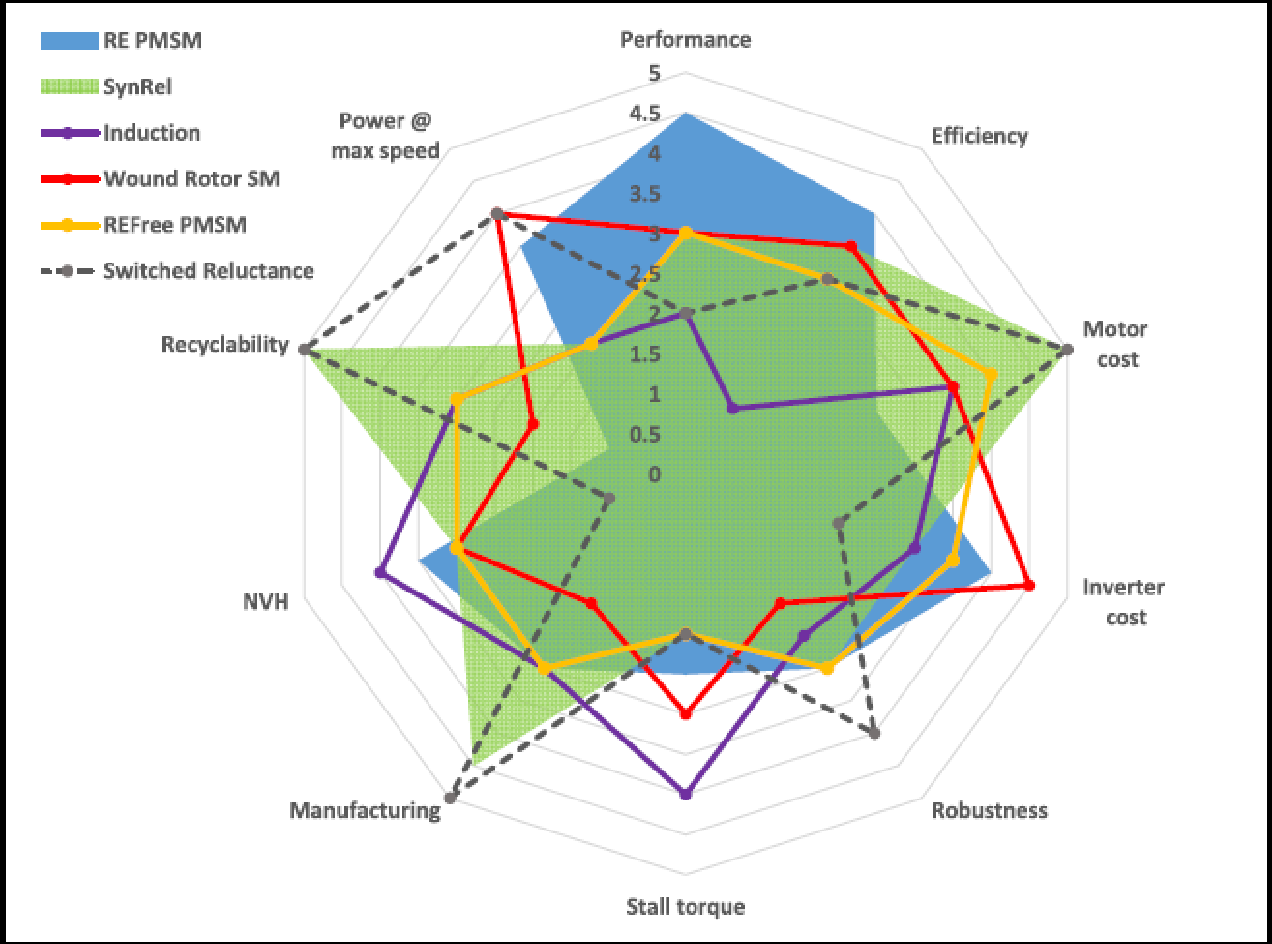
- Evs Powertrain architecture



Traction Motors For EVs*

- Rare earth free solutions score high at:
  - Manufacturing
  - Robustness
  - Stall torque
  - Recyclability
  - Motor/inverter Cost

- Drawbacks compared to PM solutions:
  - Performance
  - Efficiency

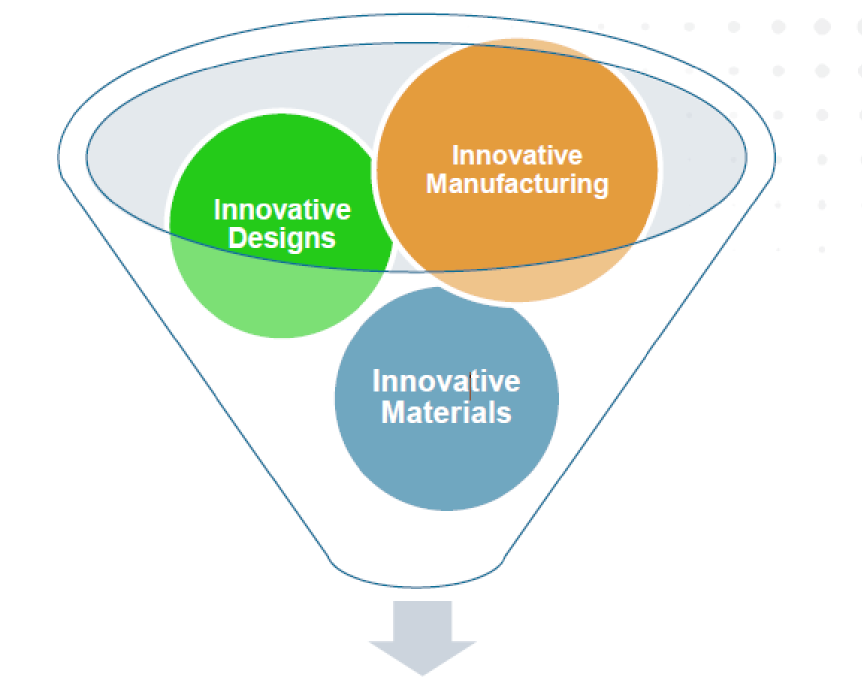


* Adoption of the Synchronous Reluctance Motor in Electric Vehicles: A Focus on the Flux Weakening Capability, Digital Object Identifier 10.1109/TTE.2022.3204435

Introduction to Digital Design Process

Introduction to Digital Design Aspects

- Development of an E-mobility powertrain is a complex systems problem
- Achieving an optimal system design requires evaluation of many different concepts and topologies as well as detailed understanding of the system interactions
- These interactions are typically cross specialism or discipline, involve different teams and often require multi-physics analysis
- Targeted metrics
  - Source cooling
  - High power density
  - High efficiency
  - Compact
  - Reliable
  - Meets roadmap to commercialization

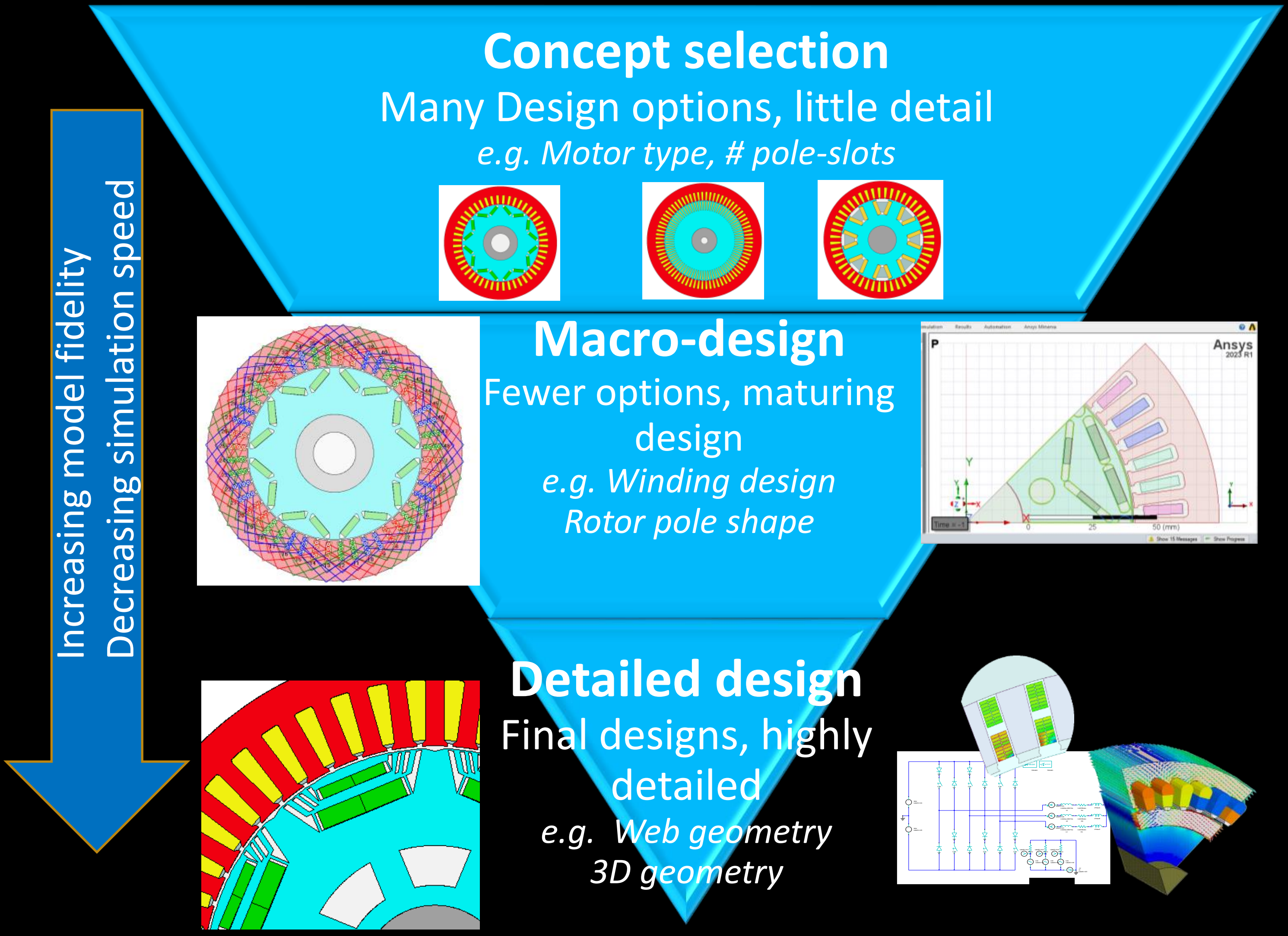


Electric Motors Digital Design Targets

- Higher efficiency
- Increased torque and power densities
- Reduced costs
- Increasing volumes and mass production
- Increased integration
- Shorter development cycles

Model Fidelity in Motor Digital Design Process

- Design Process can be seen as a Funnel
- Many design options to start, few designs at the end
- Increasing level of model fidelity required as designs mature
- Simulation time needs to adjust to number of designs analyzed
- Correlation of concept design models with detailed analysis is crucial



Managing Design Space Complexity

- Even changing a single design parameter will affect a large range of performance criteria in conflicting ways
- Typically, we will have 15 or more design parameters in a concept design process
- With all this comprehensive analysis included how can an engineer make decisions and navigate the design space?

Split ratio (Di/Do) modification

Performance criteria	Impact of design parameter modification
Peak power	↑
Peak torque	↑
Continuous power	↓
Torque ripple	↑
Drive cycle efficiency	↑
Rotor stress	↑
NVH	↑
Cost	↓

Traction Induction Machine Case

Traction Induction Motor – Case Study*

$$T = \frac{\pi}{2\sqrt{2}} k_{w1} B_1 A_{rms} D^2 L$$

T = torque, B_1 = fundamental airgap flux density (magnetic loading), A = the electrical loading, D^2 L = rotor volume

- Even if IM presents a lower efficiency and torque density than PM motors, the technology is well-established in the automotive industry, and it still represents an attractive and feasible solution for Evs

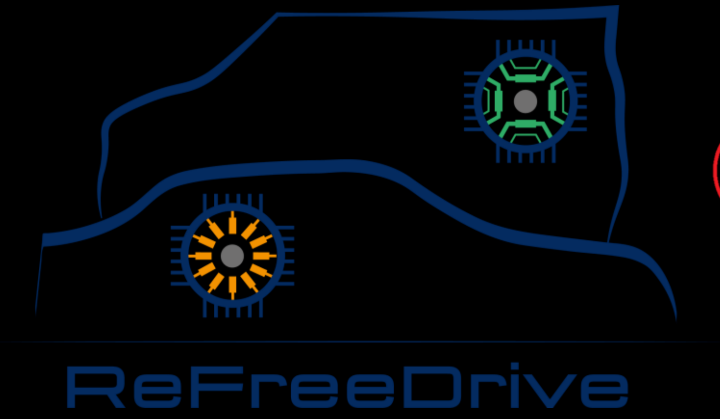
- Simplicity, robustness, versatility, cost-effectiveness, fault-tolerant capabilities

- Significant improvements can be achieved through detailed digital design

*) Design of Induction Motors With Flat Wires and Copper Rotor for E-Vehicles Traction System - https://doi.org/10.1109/TIA.2023.3256391

ReFreeDrive Project Overview*

- Development of the next-gen of electric powertrains, focusing on rare-earth free traction motors.
- Induction Motor (IM) technology considered a potential candidate.



- Copper rotor IM

- High speed capability

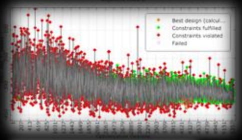
- Low cost manufacturing

- Die-casted / Fabricated roto

- Hairpin winding technology

- Low cost / loss materials

- Design optimization

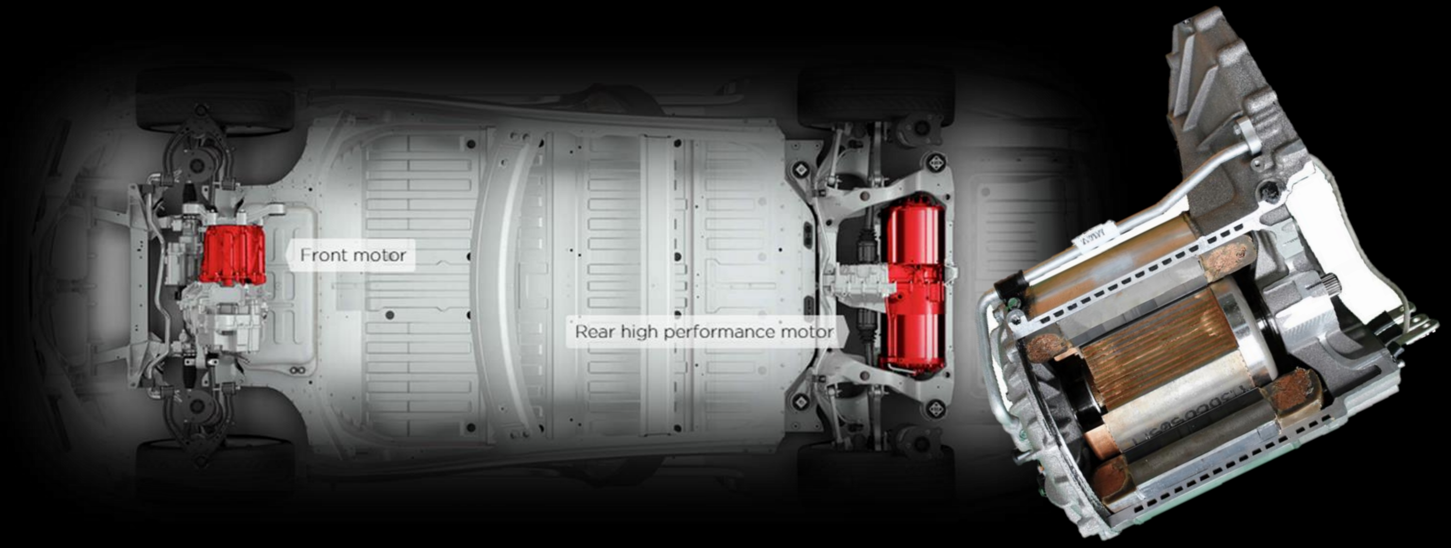


- Rotor cooling

*) RefreeDrive. (2021). *Rare Earth Free E-Drives Featuring Low Cost Manufacturing*: https://www.refreedrive.eu

Specifications

- Reference: Tesla 60S copper rotor induction motor.

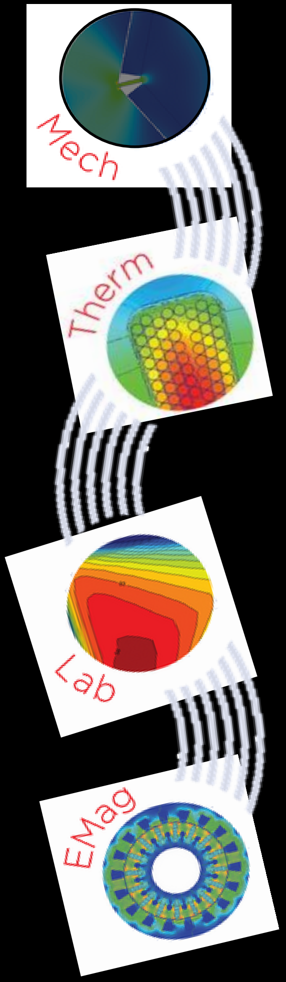


- Key Performance Indicators (KPIs)

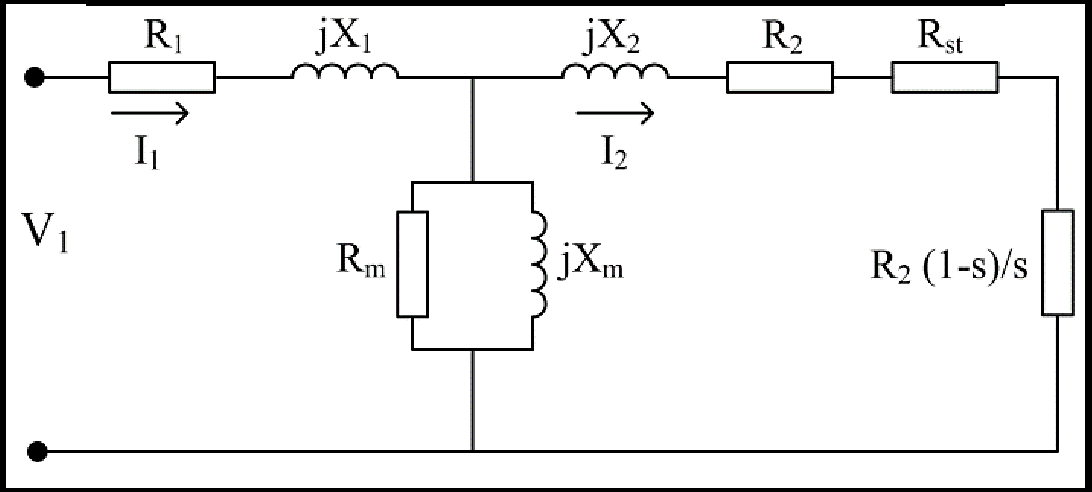
Parameter	Tesla 60S	Target	Unit
Specific power	3.3	≥ 4.3	kW/kg
Power density	-	≥ 8.0	kW/l
Specific torque	6.3	≥ 8.2	Nm/kg
Torque density	-	≥ 15.4	Nm/l
Peak efficiency	93	≥ 96	%

Design Workflow

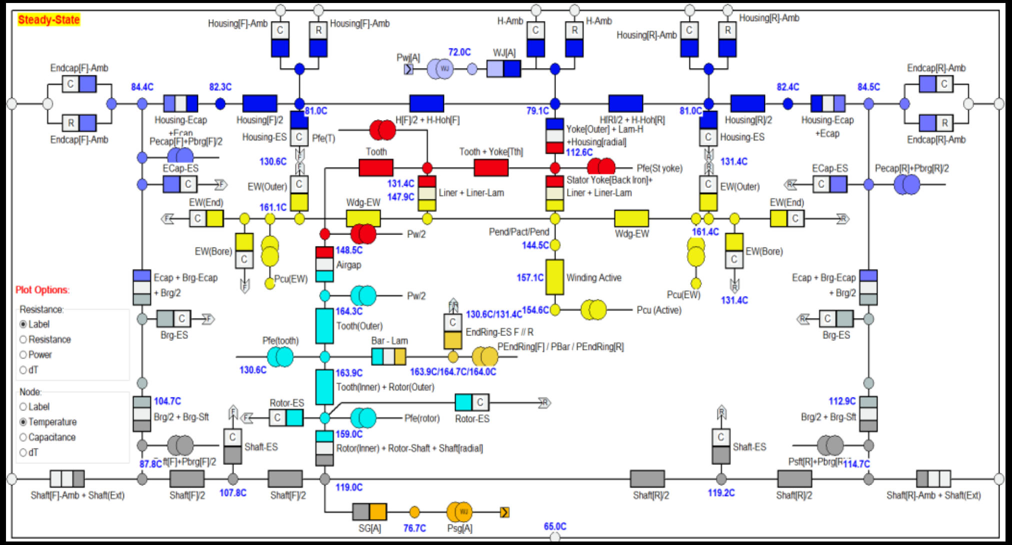
- A multiphysics optimization process is adopted to split the design space in an effective way:
  - Electromagnetic design
  - Thermal design
  - Mechanical design
- The machine's performance are calculated within its electrical and thermal limits.



IM Analytical Magnetic Circuit

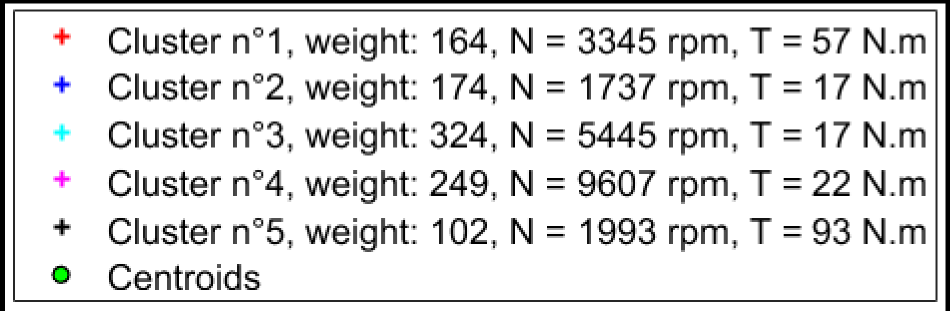


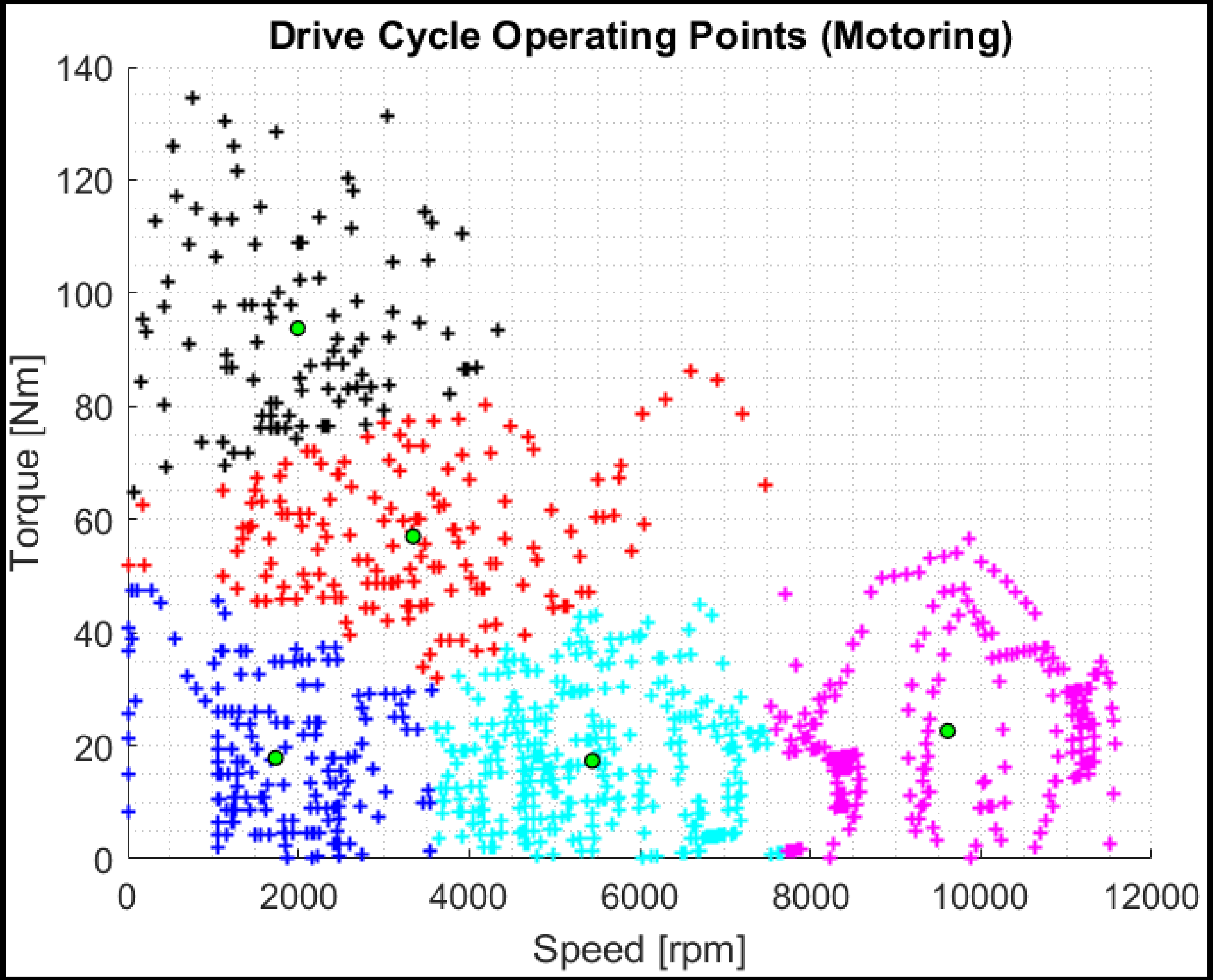
Lumped Parameter Thermal Network



Design Workflow

- The efficiency over the WLTP3 drive cycle is evaluated using five characteristic operating points.
- This clustering method allows to reduce significantly the simulation time





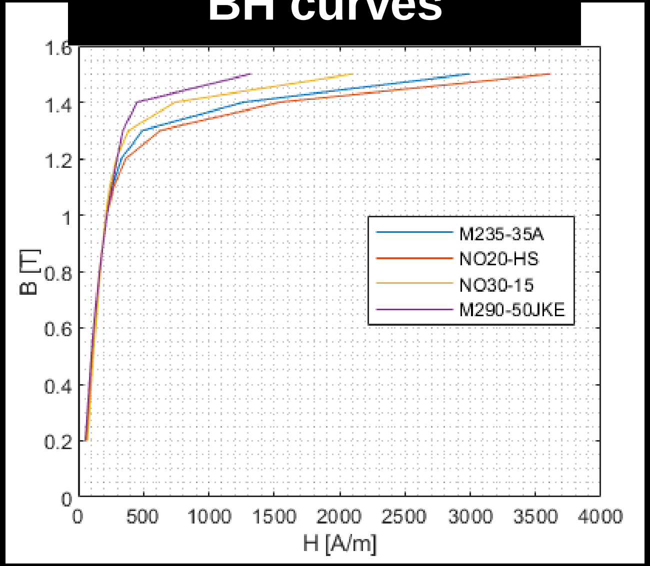
- Efficiency over WLTP3 Drive Cycle

Electromagnetic Design

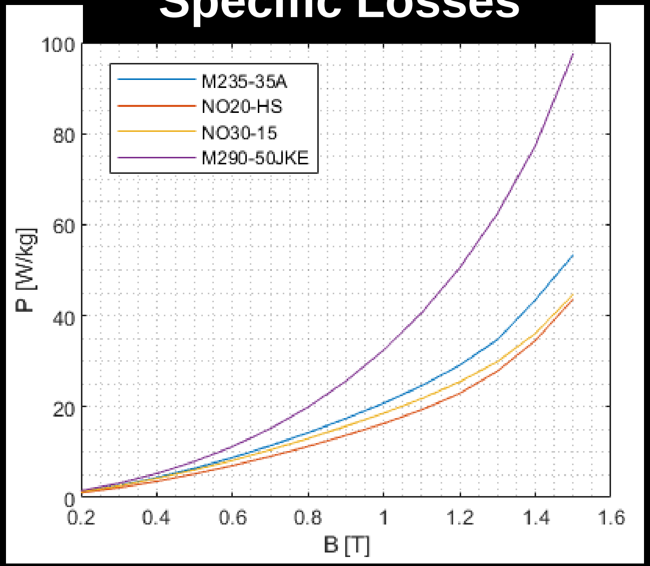
Preliminary Design Choices

- Machine topology:
  - 4-pole, 36-slot, 50-bar
- Geometry:
  - Stator outer diameter (mm) = 190
- Materials
  - M235-35A steel (rotor & stator)
  - CuAg0.04 (fabricated rotor cage)
  - Cu-ETP (die-casted rotor cage)
- Stator winding:
  - Turns / Phase = 12
  - Slot fill factor (%) = 73

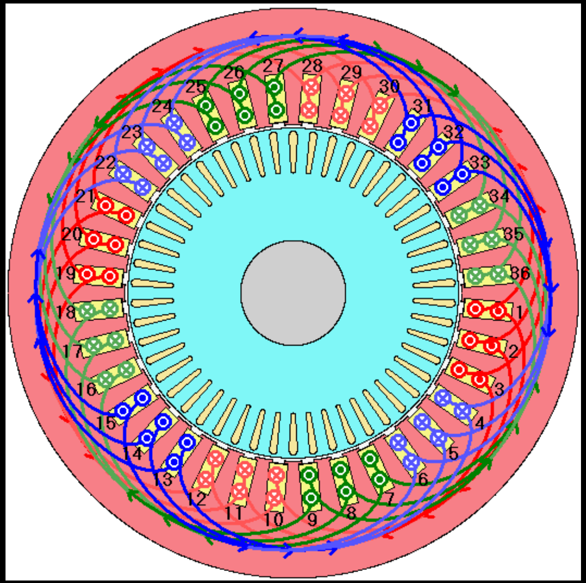
BH curves



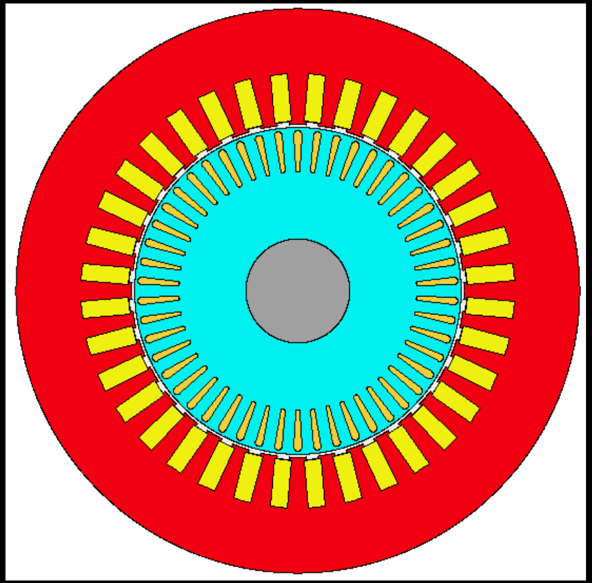
Specific Losses



Winding pattern

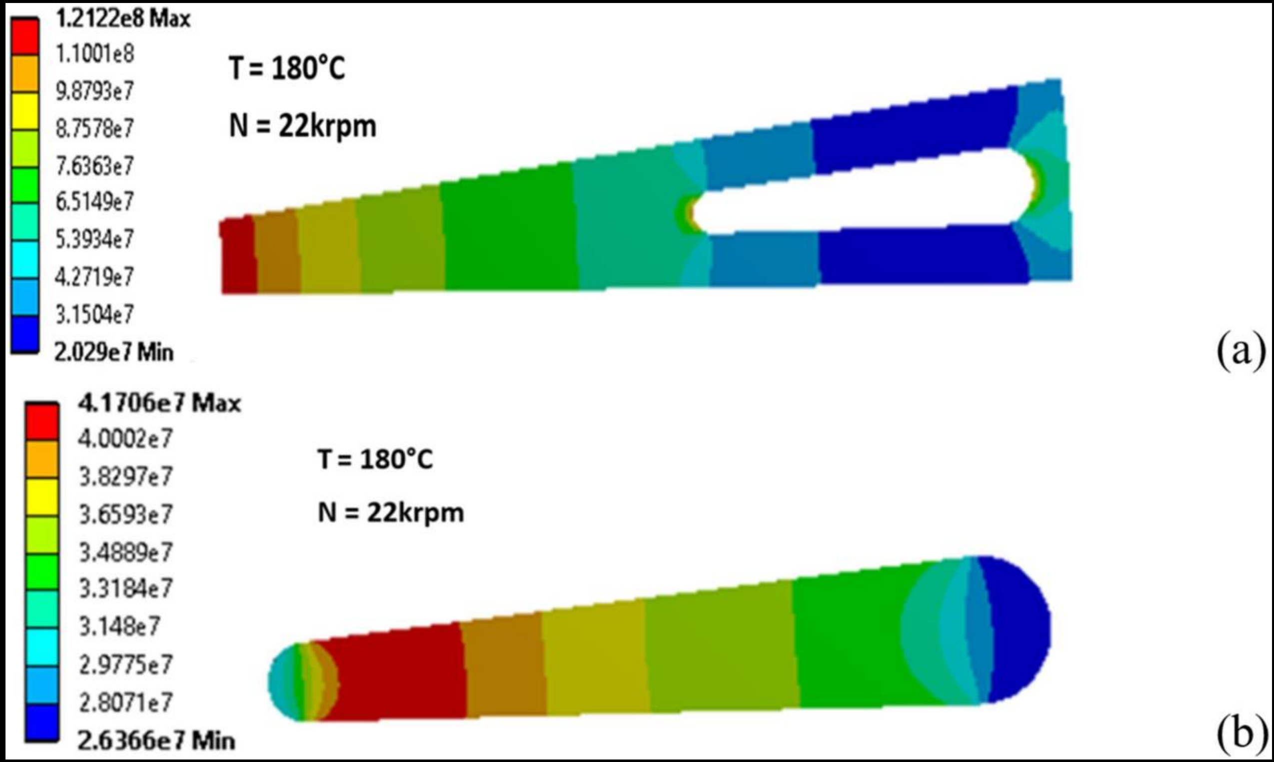


Radial Geometry

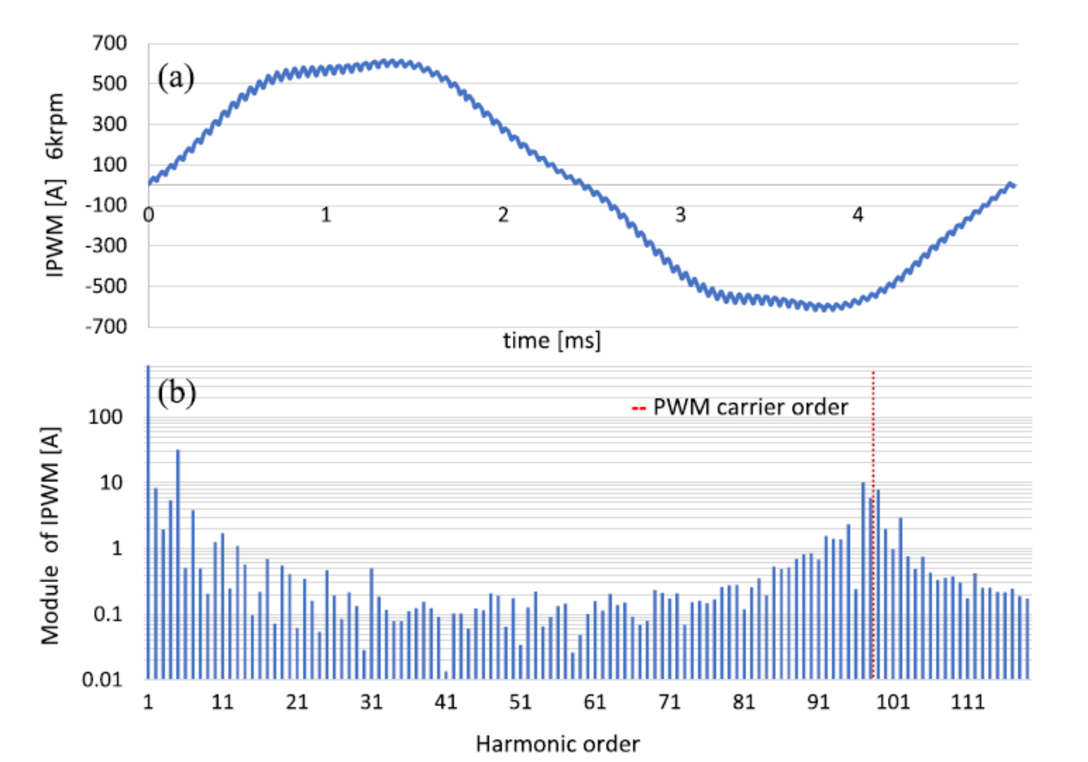


Mechanical Design

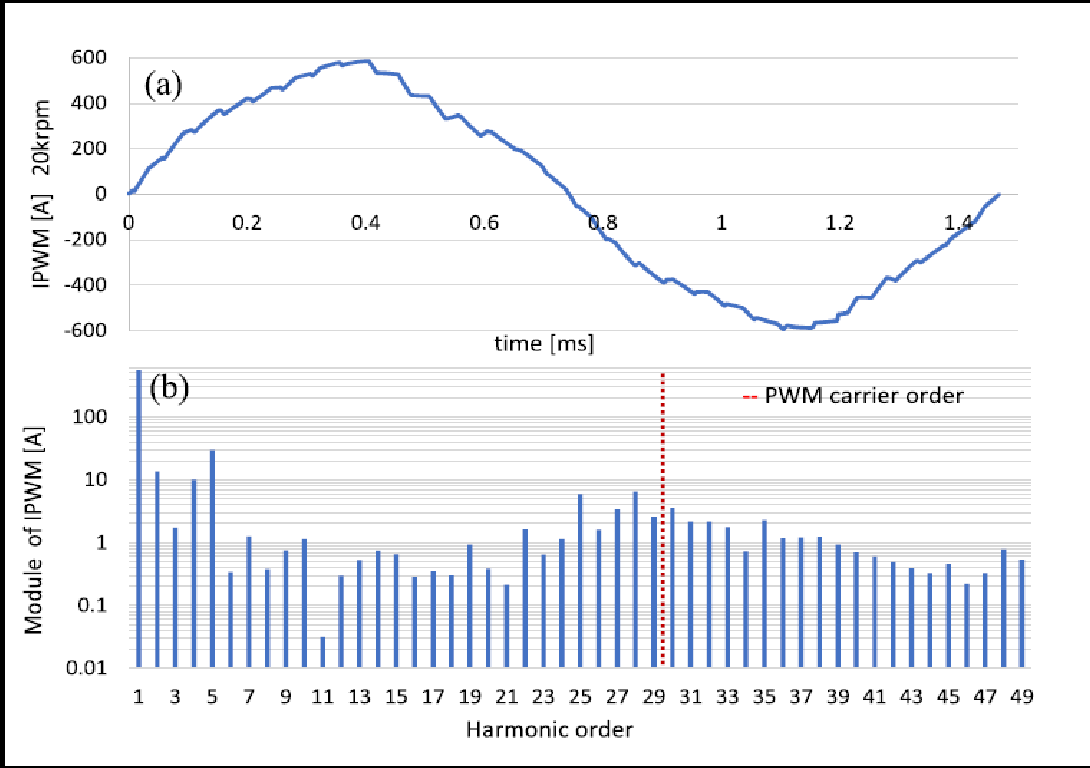
- Calculations at 20% maximum overspeed show that maximum Von Misses stress is lower than Yield stress



PWM Effect on Motor Performance



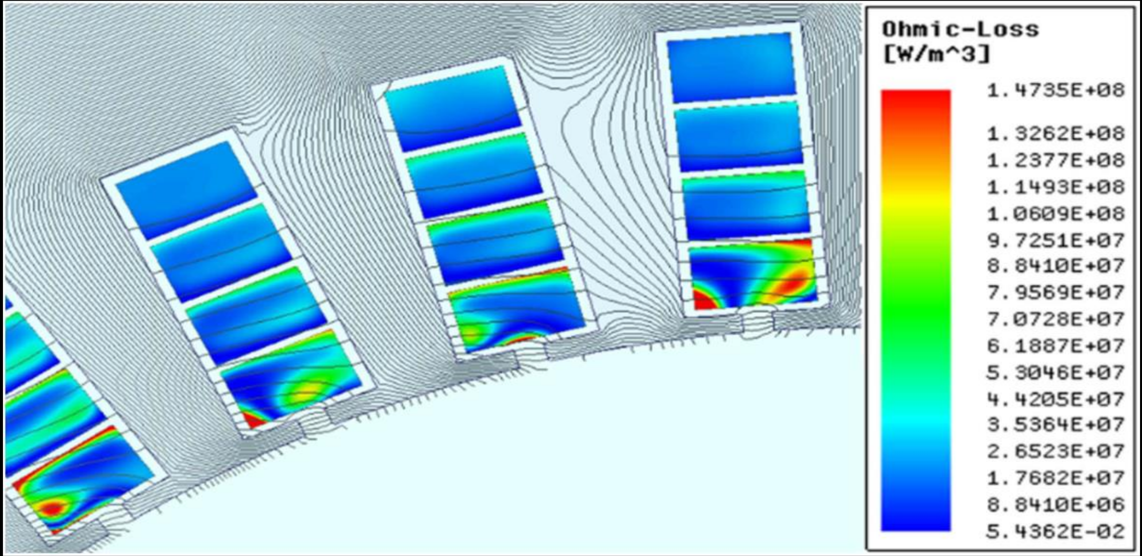
Current waveform @ 370 Nm, 6 krpm, 204.8 Hz fundamental frequency,
20 kHz PWM carrier



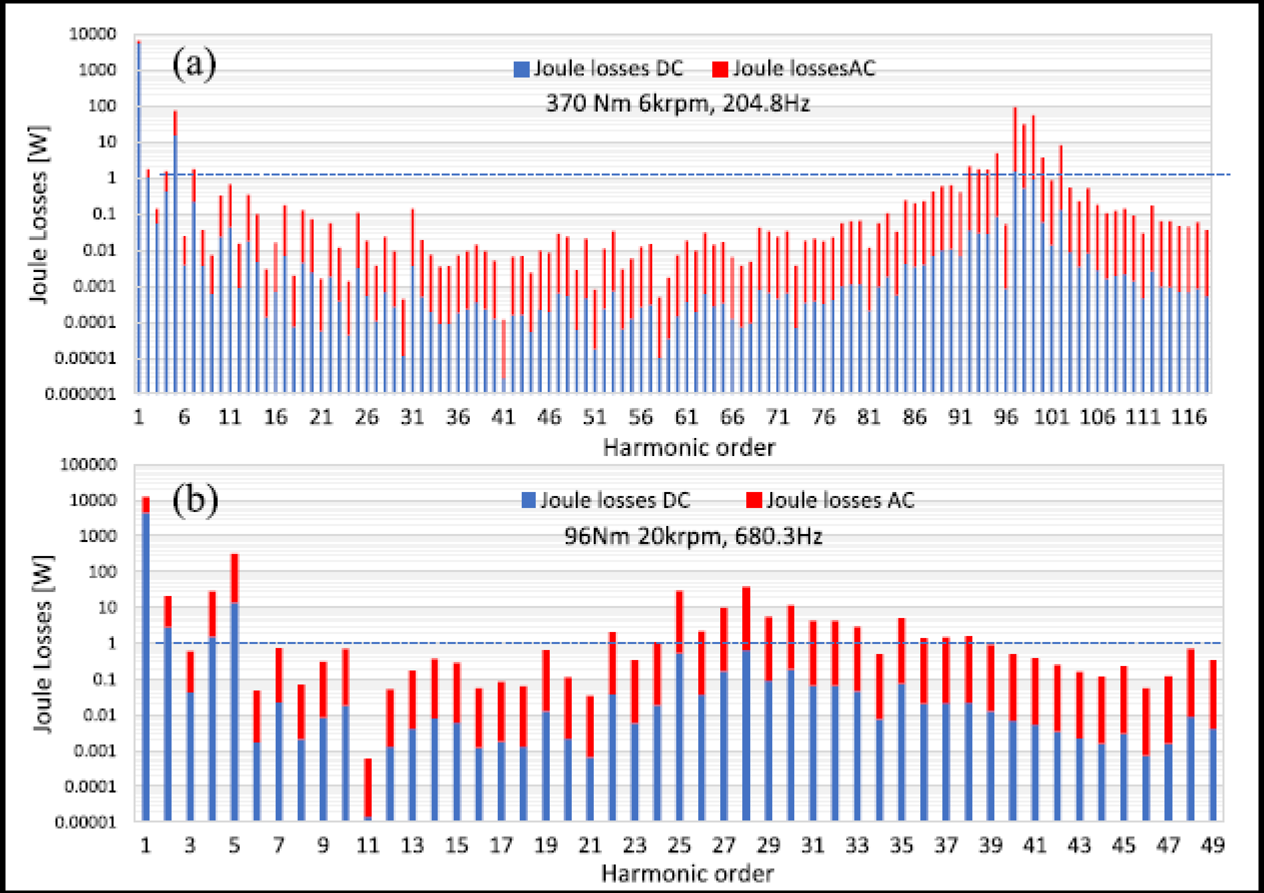
Current waveform @ 96 Nm, 20 krpm, 680.3 Hz fundamental frequency,
20 kHz PWM carrier

PWM Effect on Motor Performance

- Ohmic stator winding losses are the main loss component



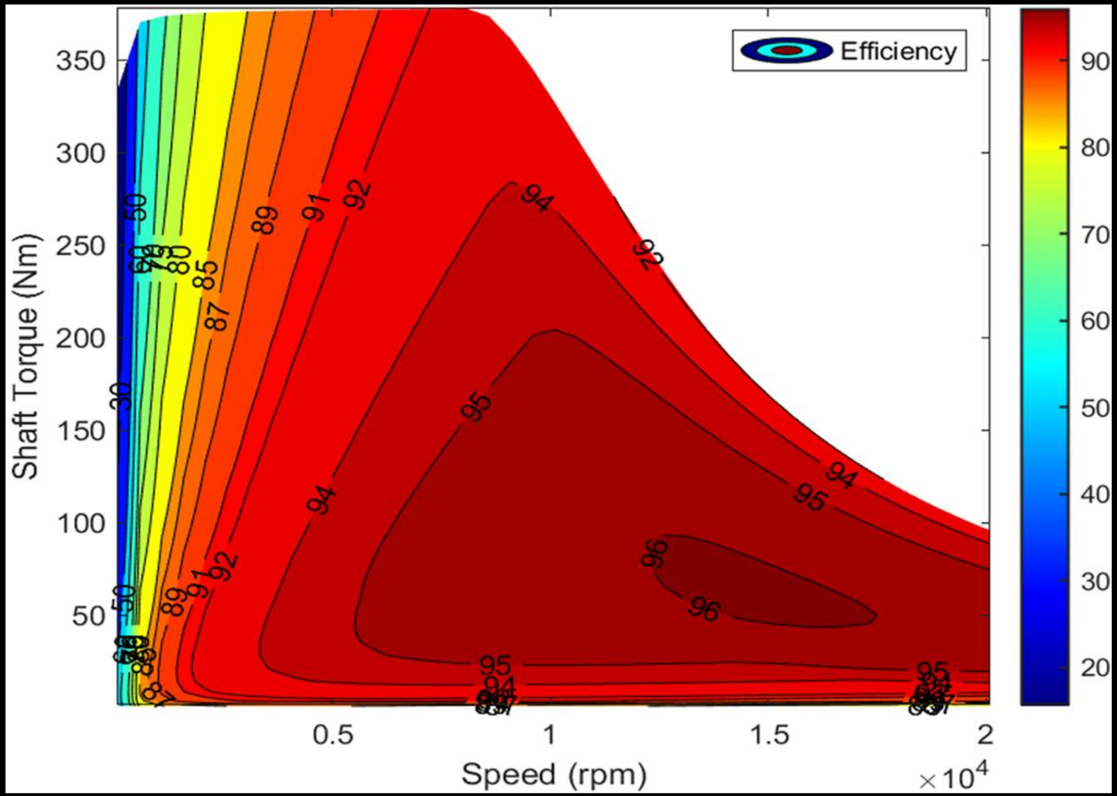
Ohmic Losses distribution @ 96 Nm, 20 krpm, 680.3 Hz fundamental frequency, 20 kHz PWM carrier

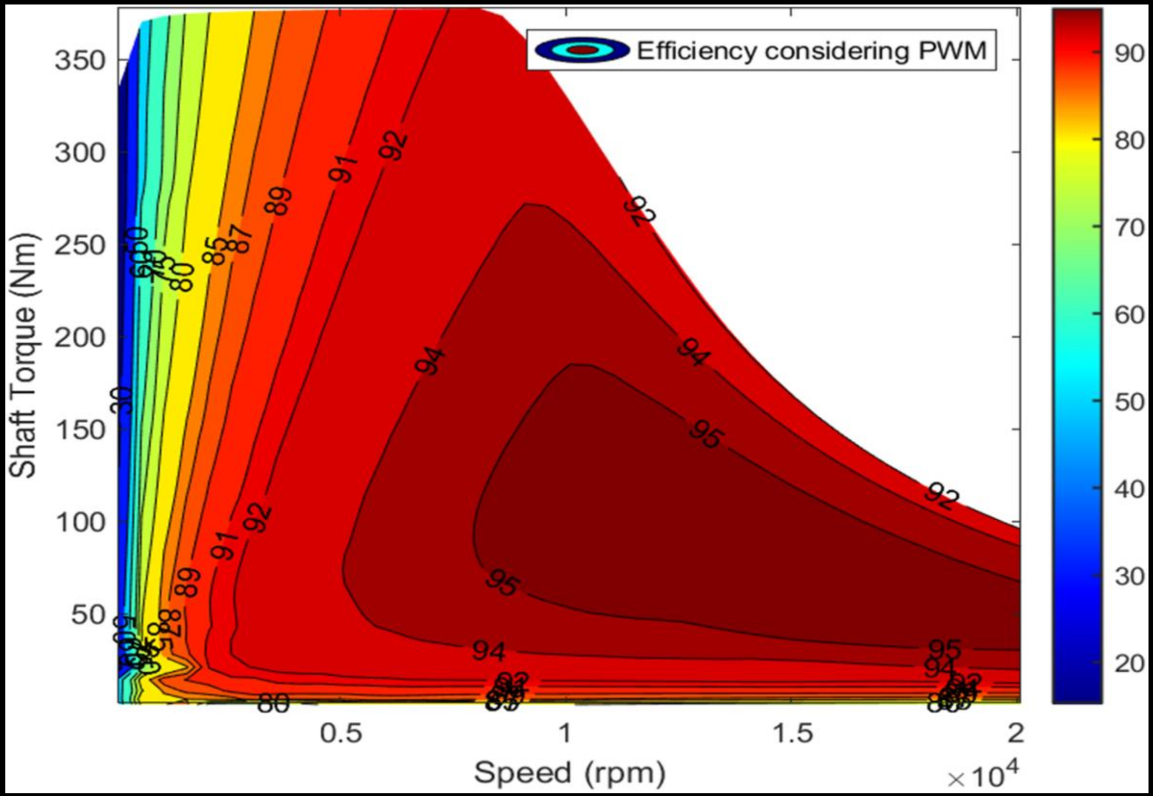


Ohmic Losses (a) 6 krpm, 204.8 Hz fundamental frequency, 20 kHz PWM carrier; (b) 20 krpm, 680.3 Hz fundamental frequency, 20 kHz PWM carrier

Electromagnetic Design

- Peak performance requirements are met and the efficiency over the WLTP3 drive cycle is about 95.05% (motoring).

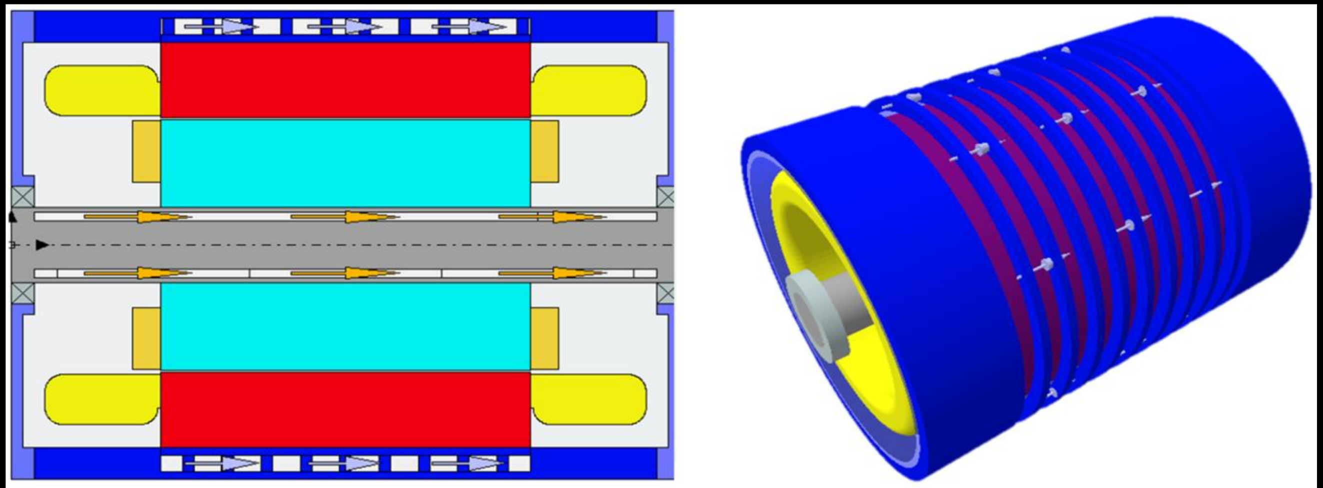




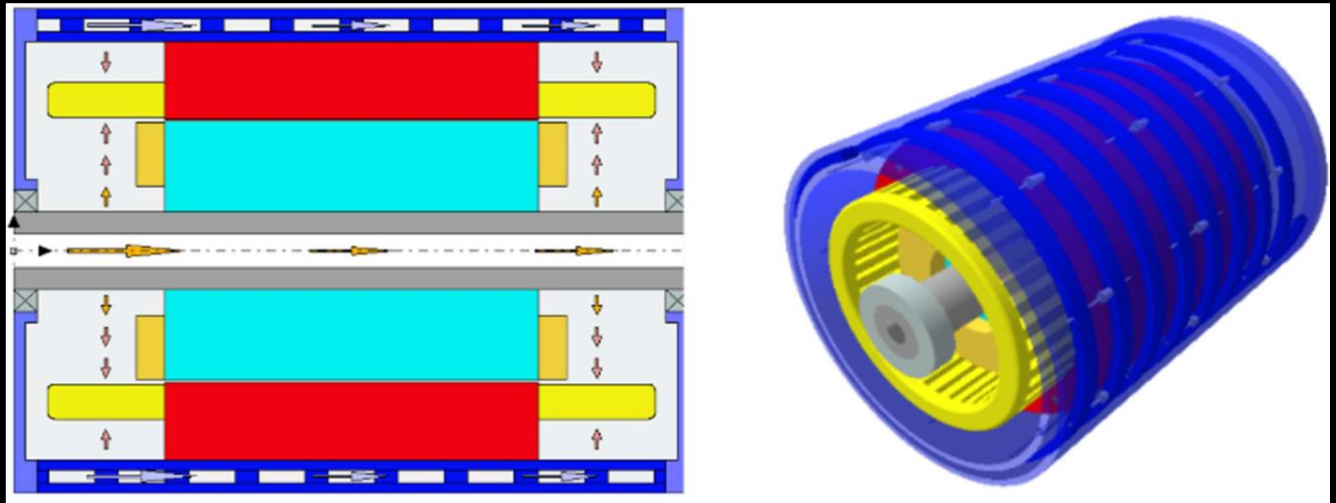
Thermal Design

- Various cooling systems considered:
- Water Jacket + Spiral Groove
- Water Jacket + Oil Spray

Parameter	Unit	SYSTEM (1) WJ+SG		SYSTEM (2) WJ+OS	
		WJ	**SG**	**WJ**	**SG**
Fluid inlet temperature	°C	75 (EWG)	75 (EWG)	90 (ATF)	90 (ATF)
Fluid flow rate	l/min	5.75	4.25	6	2
Pressure drop	kPa	10.42	-	15	-
Channel number	-	10	1	10	1



(a) Axial view (b) 3D view



(a) Axial view (b) 3D view

Thermal Design

- Various cooling systems considered:
- Water Jacket + Spiral Groove (1)
- Water Jacket + Oil Spray (2)

Parameter	Unit	SYSTEM (1) WJ+SG		SYSTEM (2) WJ+OS	
		WJ	**SG**	**WJ**	**SG**
Fluid inlet temperature	°C	75 (EWG)	75 (EWG)	90 (ATF)	90 (ATF)
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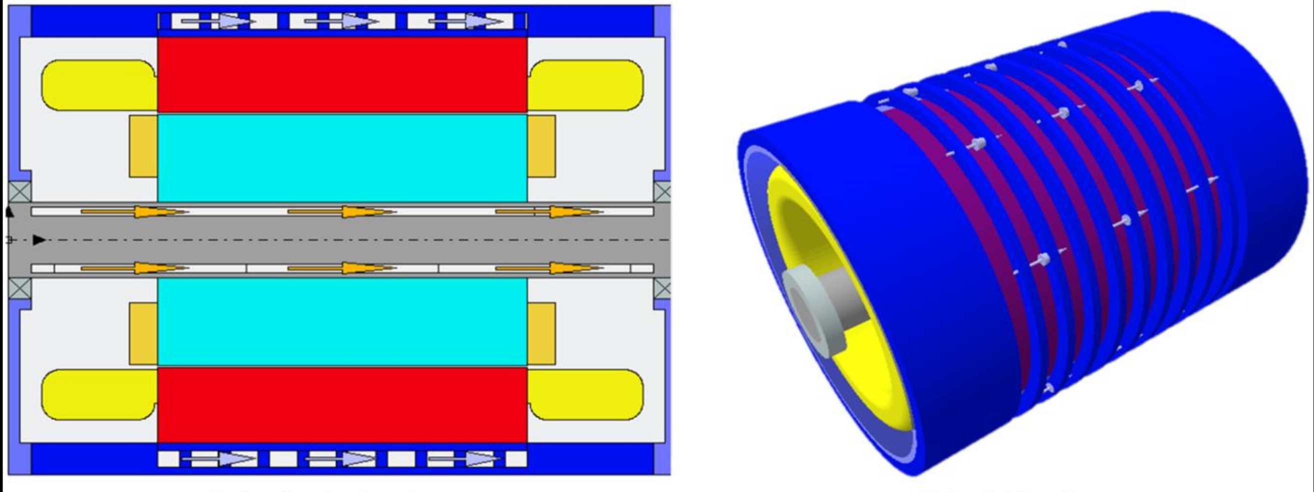
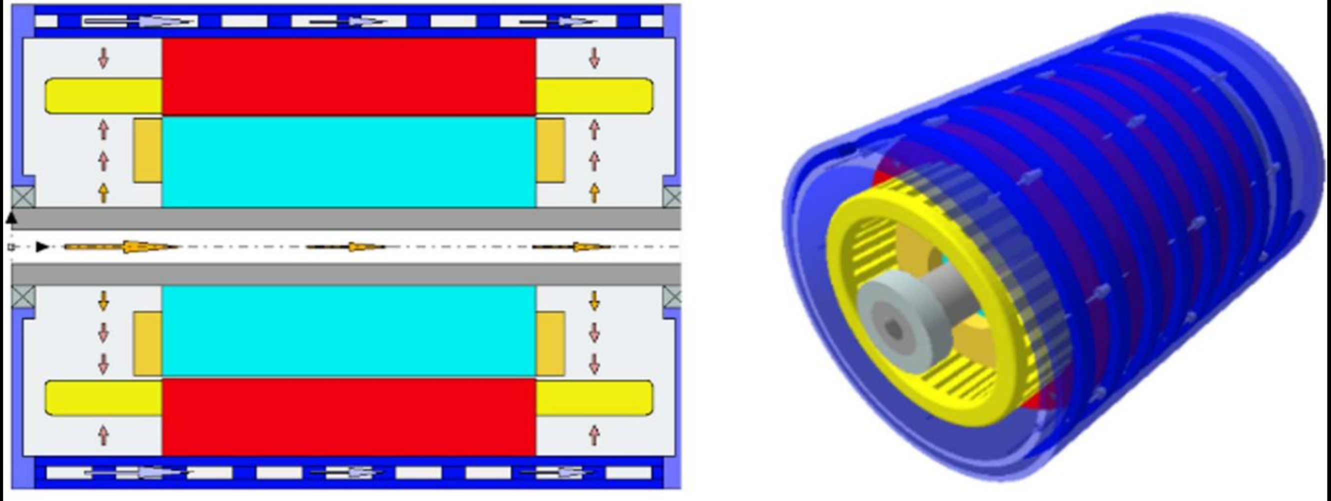


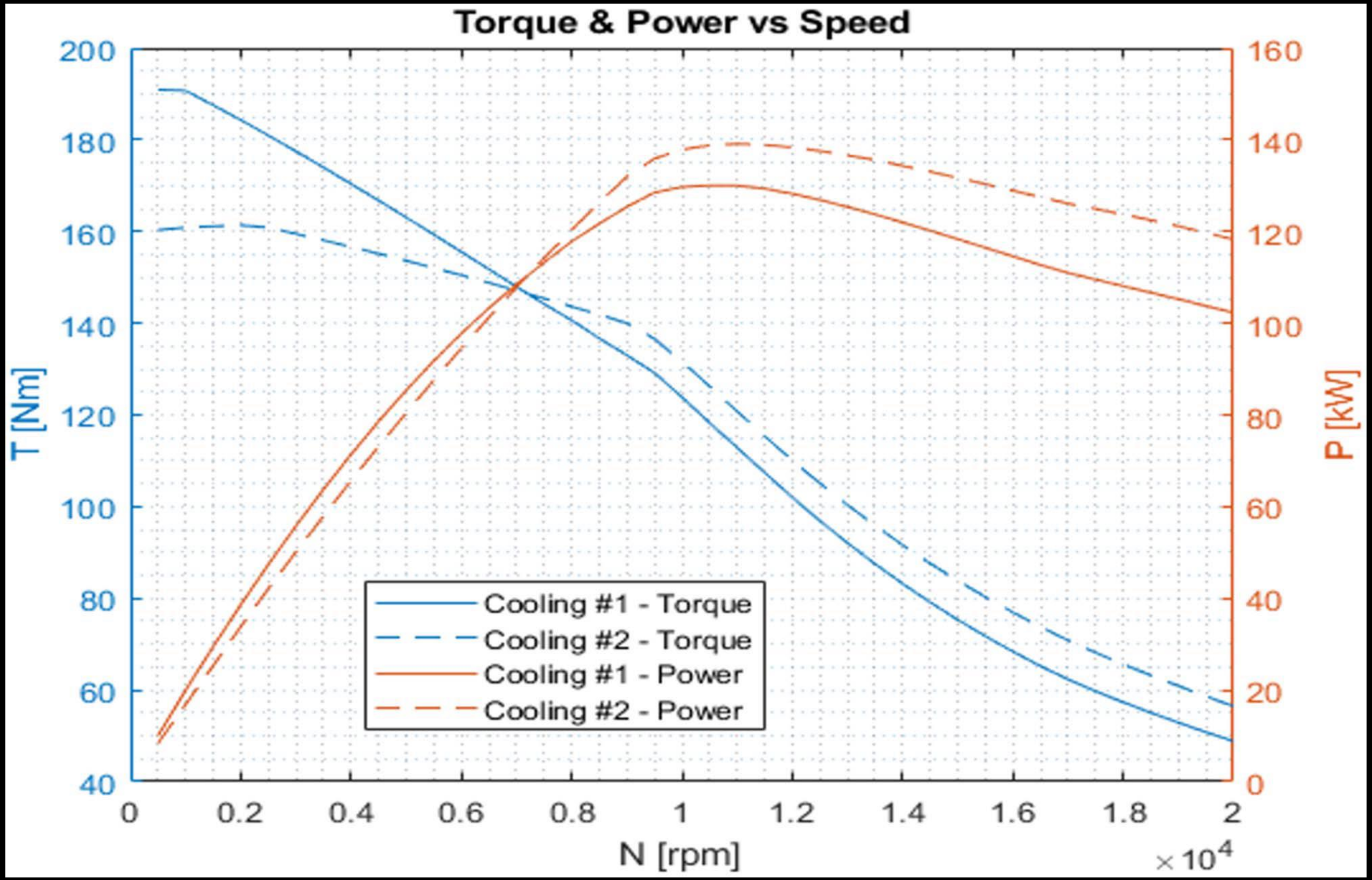
(a) Axial view (b) 3D view



(a) Axial view (b) 3D view

Thermal Design

- Continuous Performance
- Water Jacket + Spiral Groove (1)
- Water Jacket + Oil Spray (2)



Traction Synchronous Reluctance Machine Case

Traction Synchronous Reluctance Motor – Case Study*

- Torque $$T_{em} = 3p\frac{(L_d - L_q)}{2}\sin(2\psi) \Rightarrow T_{em} = 3p(L_d - L_q)I_d I_q$$
- Simplicity, robustness, versatility, cost-effectiveness, fault-tolerant capabilities
- Manufacturing process is simple and easy to implement
- Lower efficiency and power factor compared to PM or even IM
- Higher inverter and battery costs
- Improvements can be achieved through detailed digital design

*) Adoption of the Synchronous Reluctance Motor in Electric Vehicles: A Focus on the Flux Weakening Capability, Digital Object Identifier 10.1109/TTE.2022.3204435

Traction Synchronous Reluctance Motor

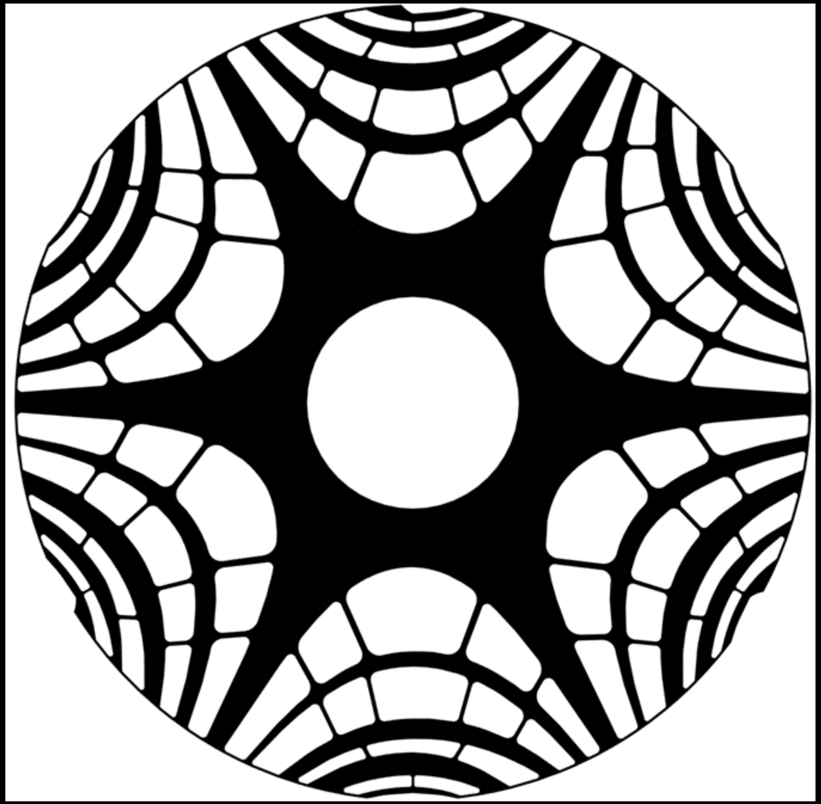
- Various solutions can be considered for SynRel motor
- In this study a comparison is made between:
  - 4 poles, 36 slots, 4 flux barriers and notch
  - 6 poles, 54 slots, 4 flux barriers and notch
  - 8 poles, 72 slots, 4 flux barriers and notch
- Operating points for multiphysics optimization:
  - P1: peak torque @ base speed
  - P2: maximum power @ maximum speed
  - P3: maximum efficiency point
  - P4: low torque and low-speed working region to maximize WLTP Class 3 cycle efficiency

Requirements		**Constraints**
DC Voltage	V	800
Specific Peak Power	kW/kg	> 4.0
Specific Peak Torque	Nm/kg	> 8.0
Peak Power	kW	200
Peak Torque	Nm	380
Peak Efficiency	%	> 95
Maximum Speed	rpm	18000
Power @ Max Speed	kW	>50
Motor Mass	kg	< 50
Outer Stator Diameter	mm	<250
Stack Length	mm	<220

Electro-Mechanical Design

Electrical Performance Comparison

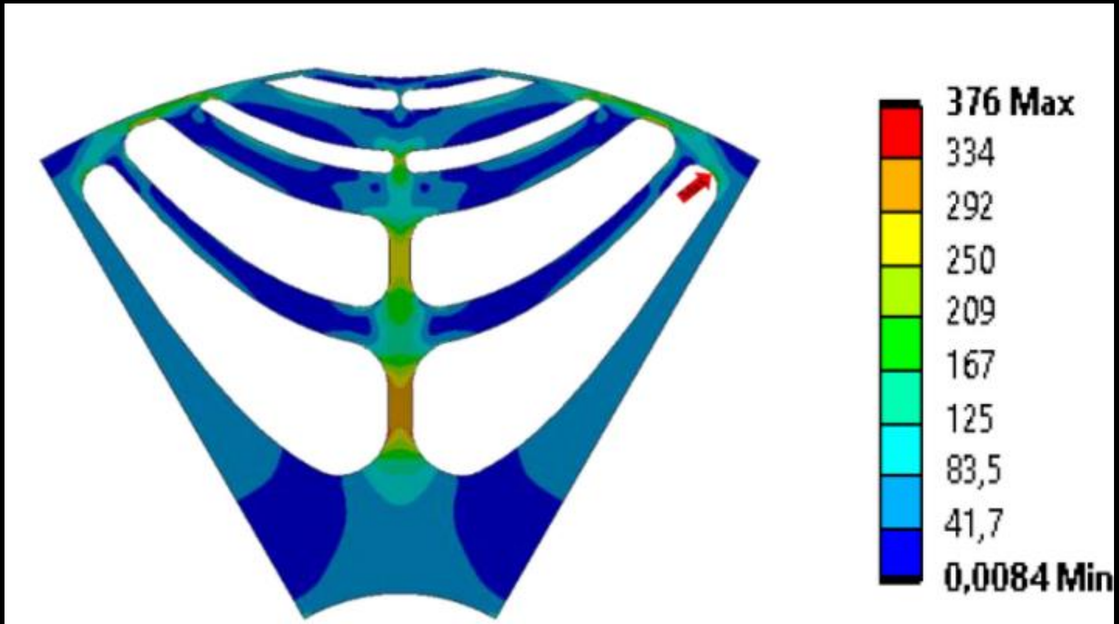
Performance	Unit	4-pole design	6-pole design	8-pole design
Torque @ P1	*Nm*	410	410	410
Power @ P2	*kW*	94	**110**	78
Torque @ P3	*Nm*	139	139	141
Torque @ P4	*Nm*	20	21	21
Ripple @ P1	%	**14**	15	**14**
Ripple @ P2	%	20	20	20
Efficiency @ P3	%	**97.3**	97.2	97.1
Efficiency @ P4	%	95	95	95



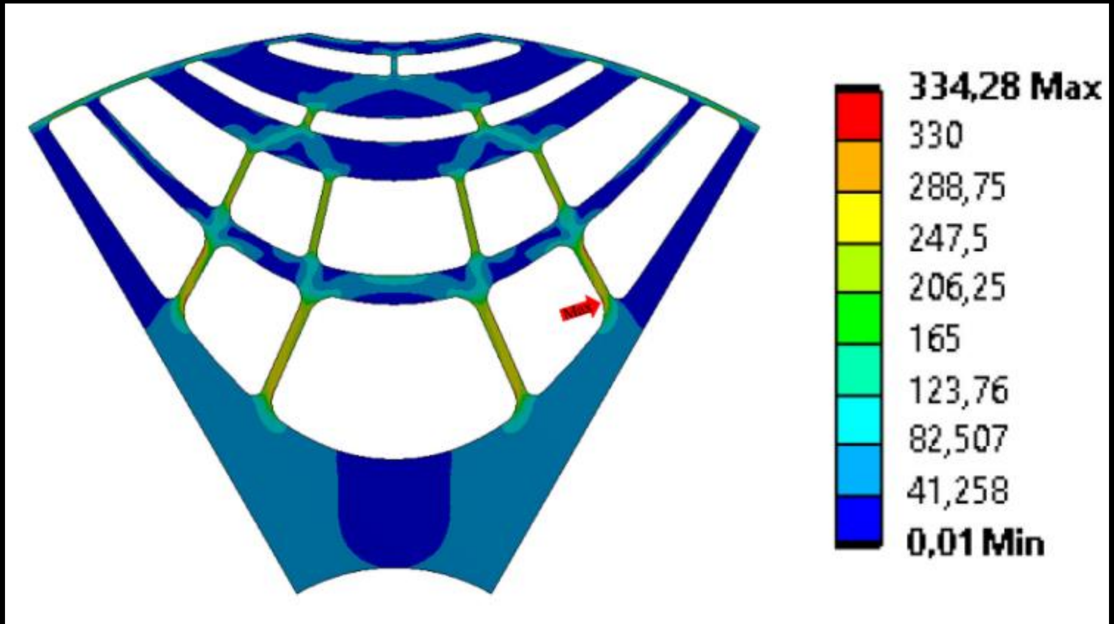
Optimized configuration for 6-pole rotor lamination

Mechanical Design

Optimisation of the rotor ribs dimensions and configuration

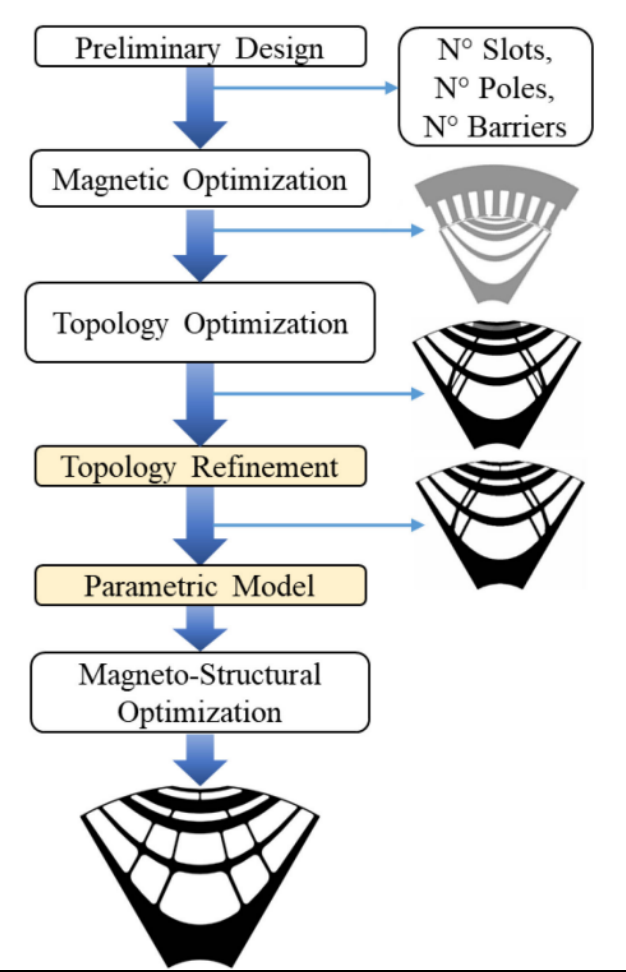


Initial Optimised design rotor lamination



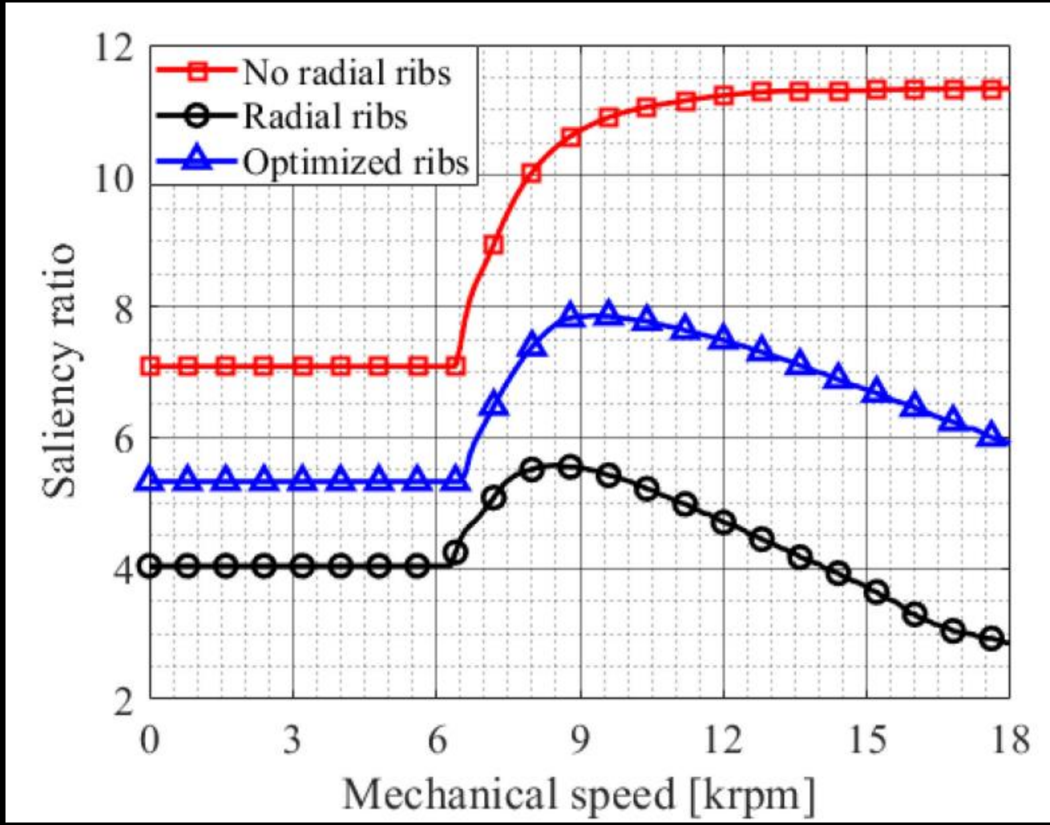
Topology Optimized design rotor lamination

Digital Design Workflow

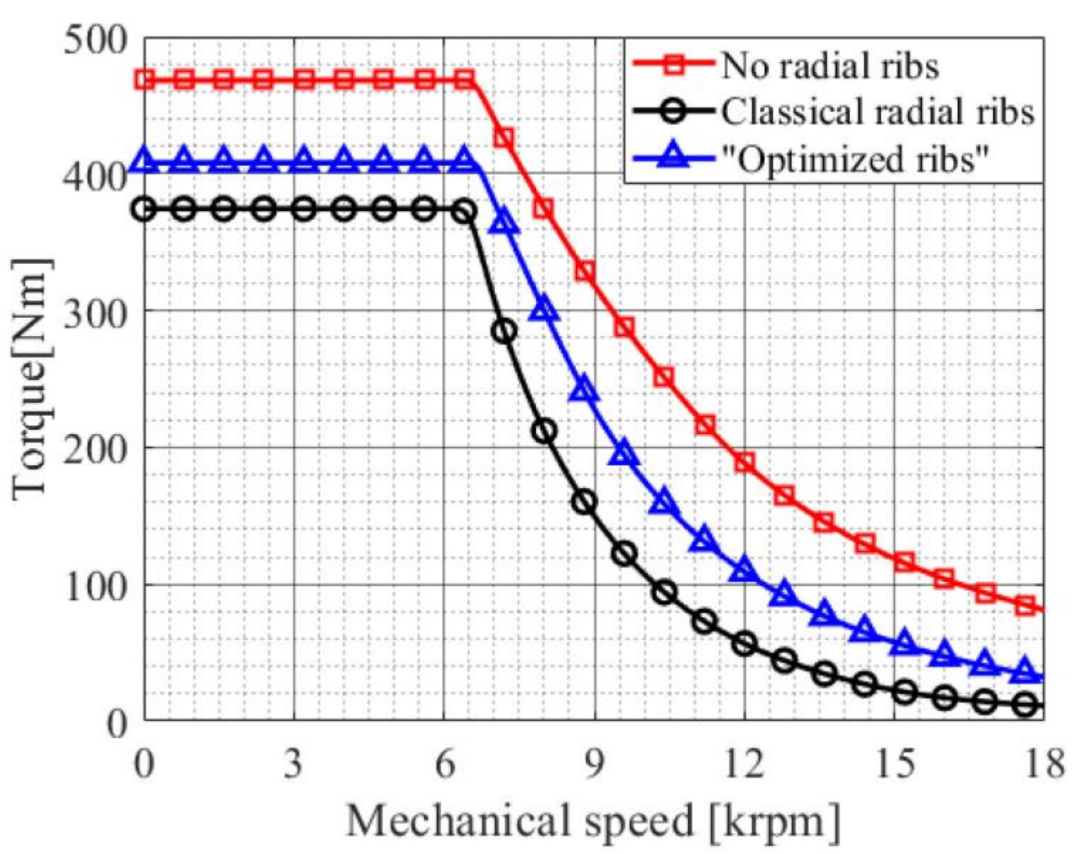


Design workflow using topology optimisation

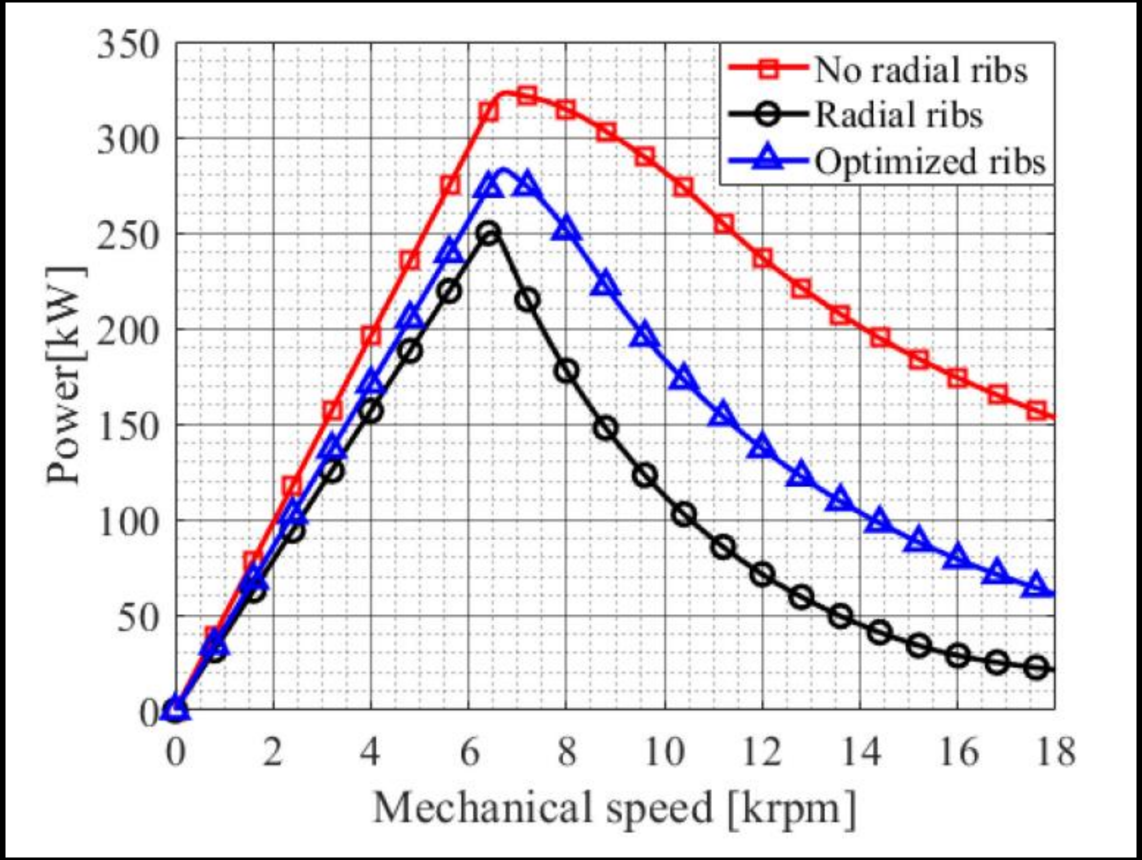
Saliency Ratio (Lq/Ld) variation with speed and topology



Electromagnetic Design Comparison

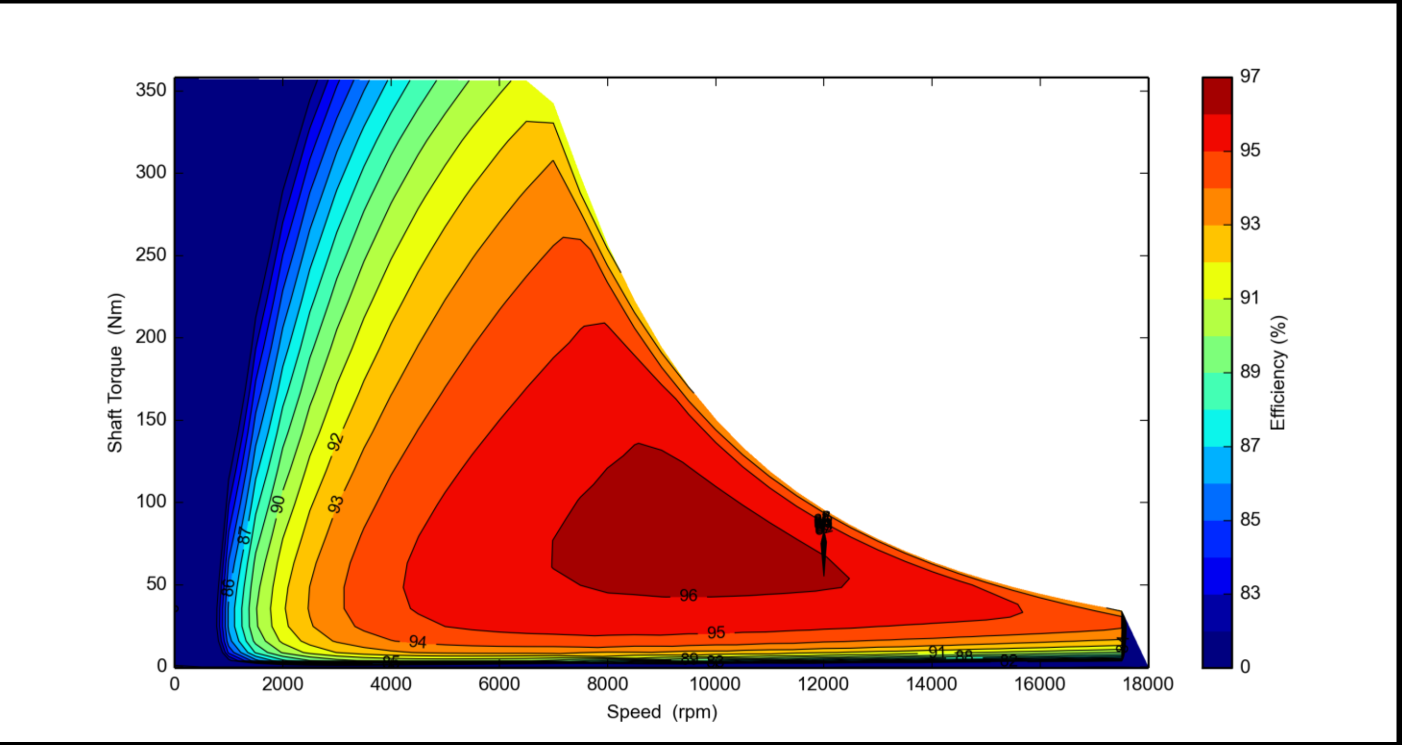


Peak Torque variation with speed and topology

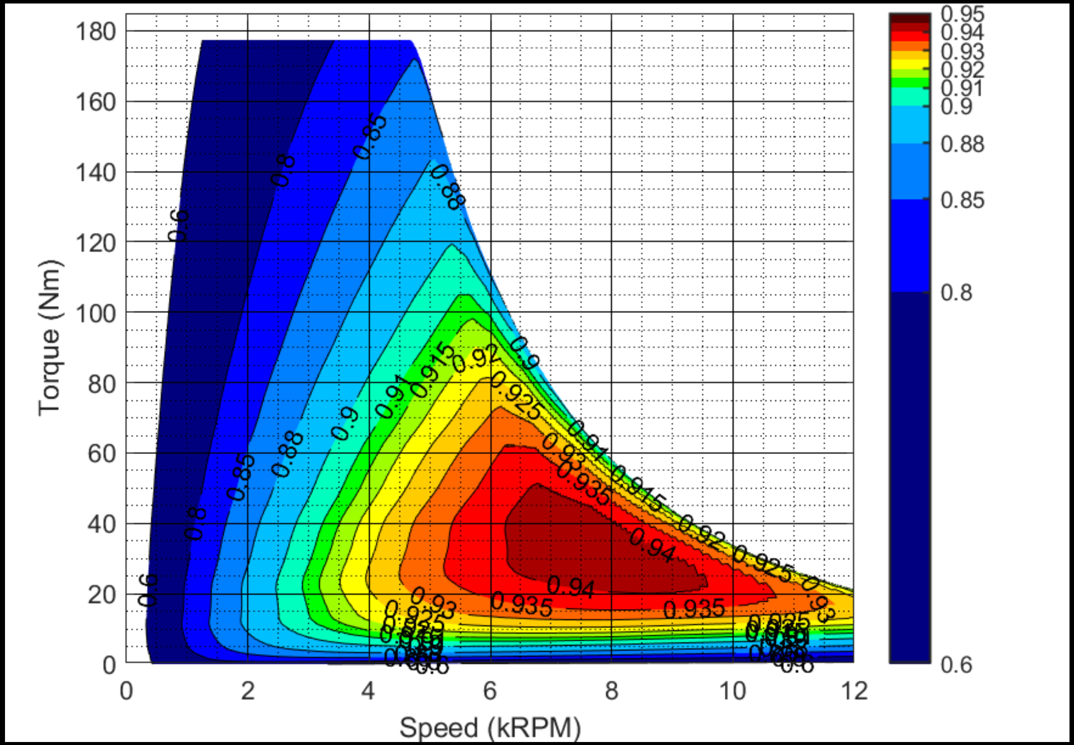


Peak Output power variation with speed and topology

Electromagnetic Design Comparison



Calculated efficiency map



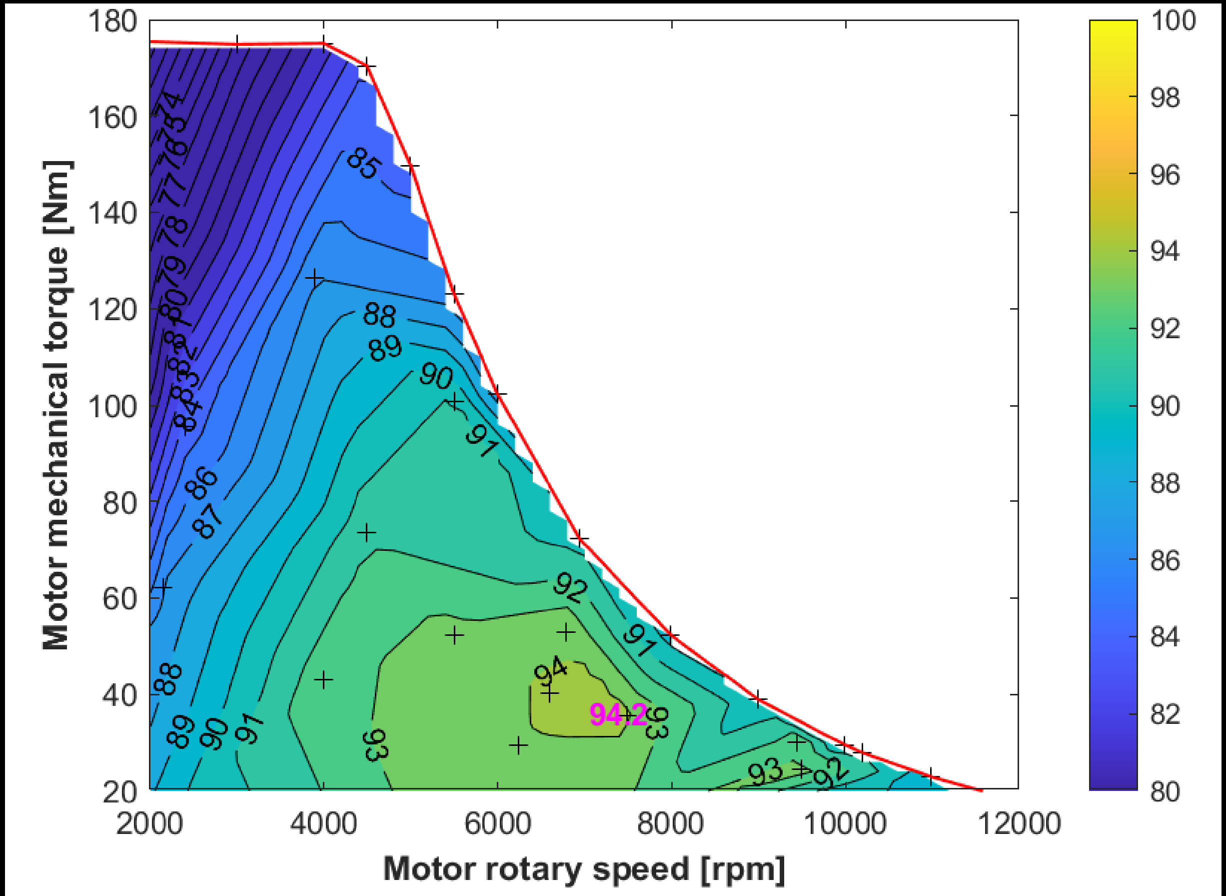
Scaled down efficiency map

Experimental Validation

Test data vs Calculated data performance

Performance	Unit	FEM	Tests
Maximum Torque	*Nm*	176.5	176.4
Phase Current	*A*	620	620
DC Voltage	*V*	350	350
DC Current (max)	*A*	300	280
$P_{\omega,m}$	*kW*	26	24
Max. Efficiency	*%*	94.4	94.3
Specific Peak Power	*kW/kg*	4.04	3.9
Specific Peak Torque	*Nm/kg*	8.8	8.7
Peak power density	*kW/l*	14.1	13.6
Peak torque density	*Nm/l*	30	29.9

Measured efficiency map



Ansys

Traction Synchronous Wound Field Machine Case

Traction Wound Field Machine – Case Study

- Torque: $$T_{em} = 3p\phi_r I\cos(\psi) + 3p\left(L_d - L_q\right)\frac{I^2}{2} sin(2\psi)$$

- Higher efficiency and torque density than IM or SynRel motors, the technology is still subject to innovation in the automotive industry, and it represents an attractive and feasible solution for Evs

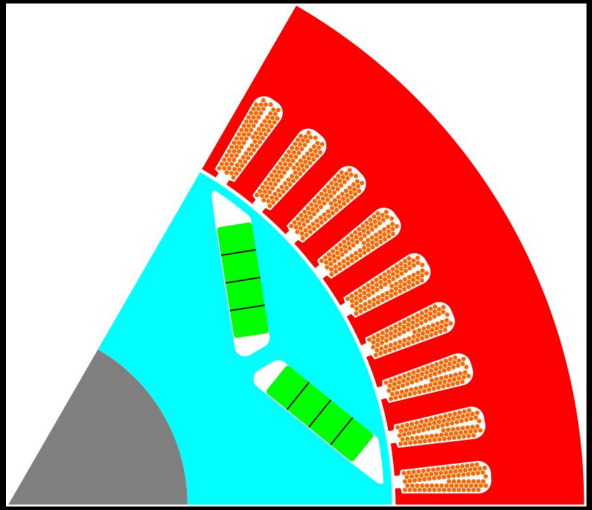
- More complex to build, higher inverter cost as both the armature and rotor excitation have to be energised

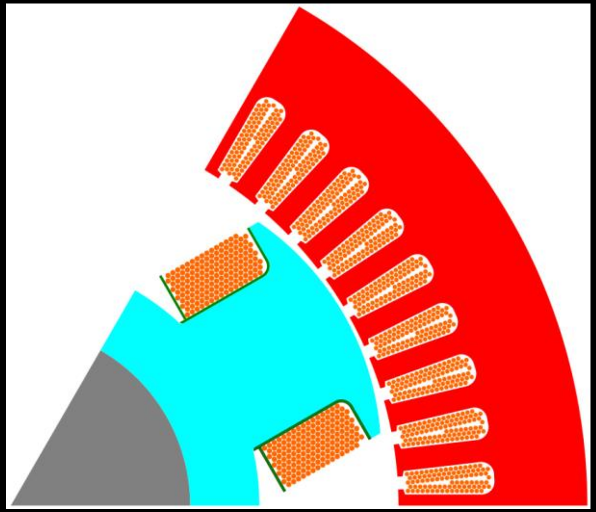
- Less fault-tolerant capabilities

- Significant improvements can be achieved through detailed digital design

Traction Wound Field Machine – Case Study (1)

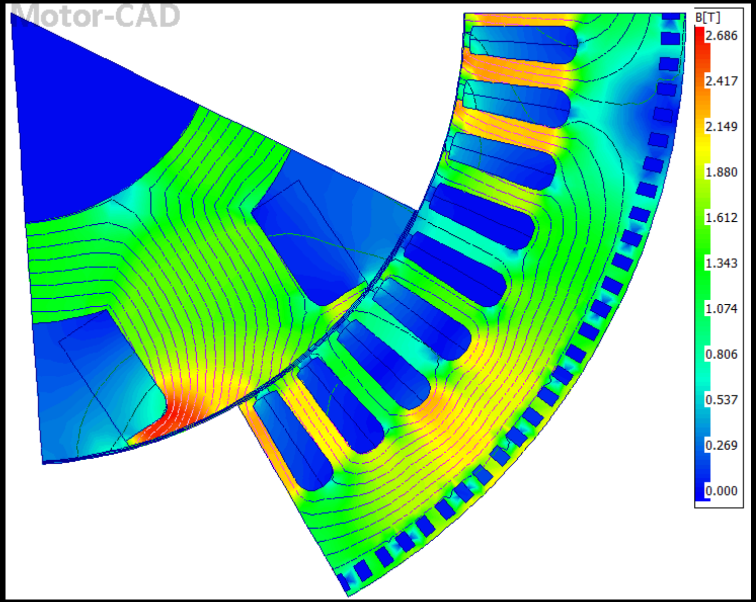
- Using as reference Tesla 3, IPM motor an equivalent WFSM machine is designed
- 54 slots, 6 poles
- Same stator as Tesla 3 IPM
- Stator water jacket cooling
- Rotor shaft spiral groove cooling

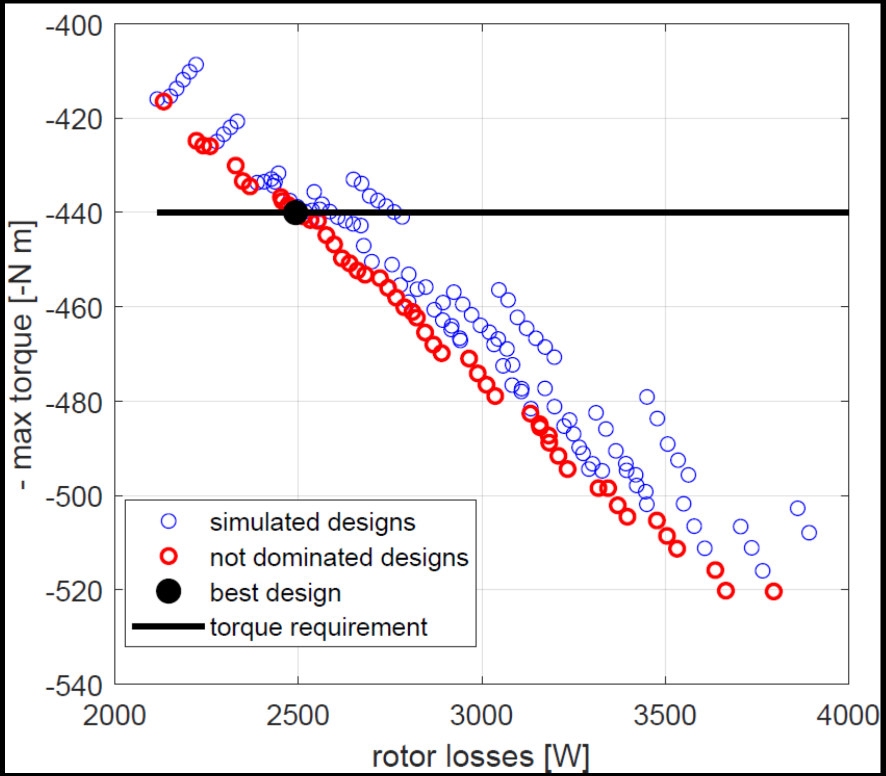




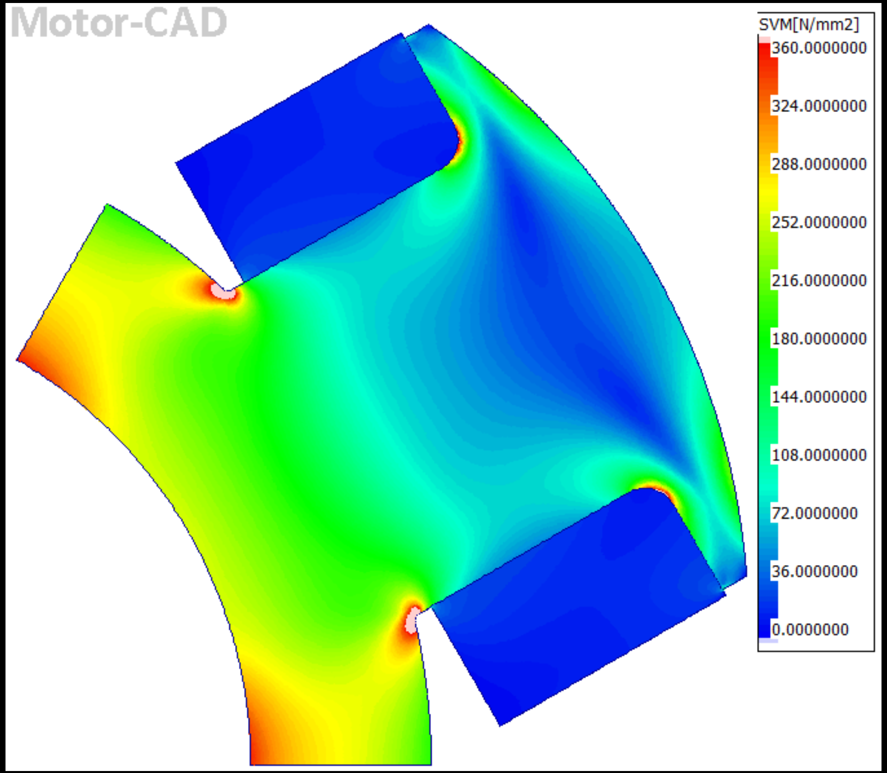
Electromagnetic Design Optimisation

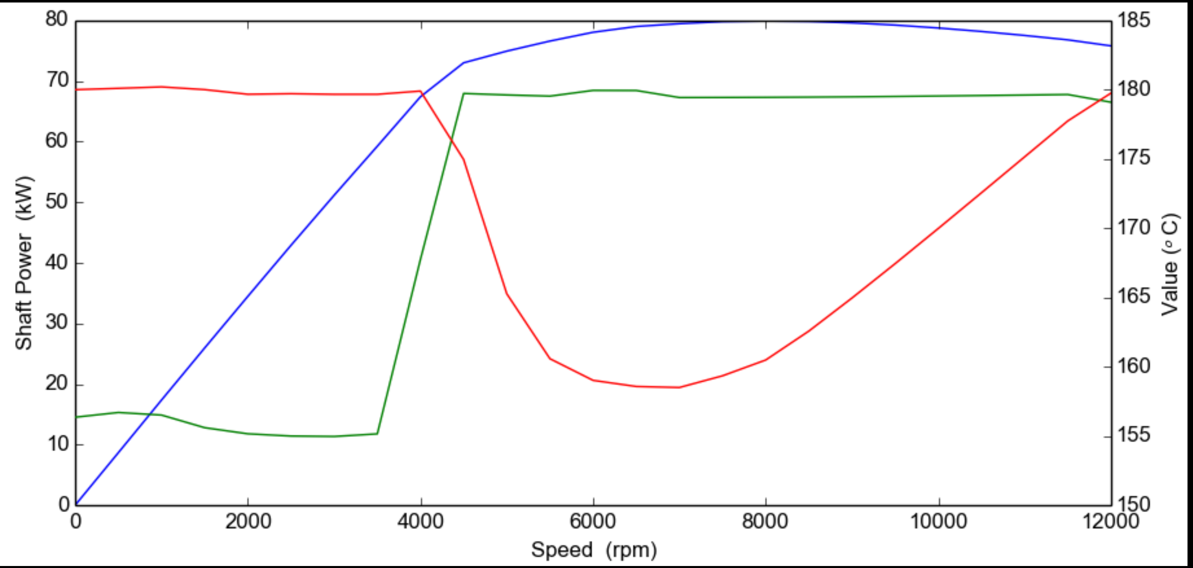
- Optimal rotor geometry
- Maximize average torque
- Minimise torque ripple
- Minimise weight
- Maximize efficiency
- Maximum Von Misses stress below Yield stress





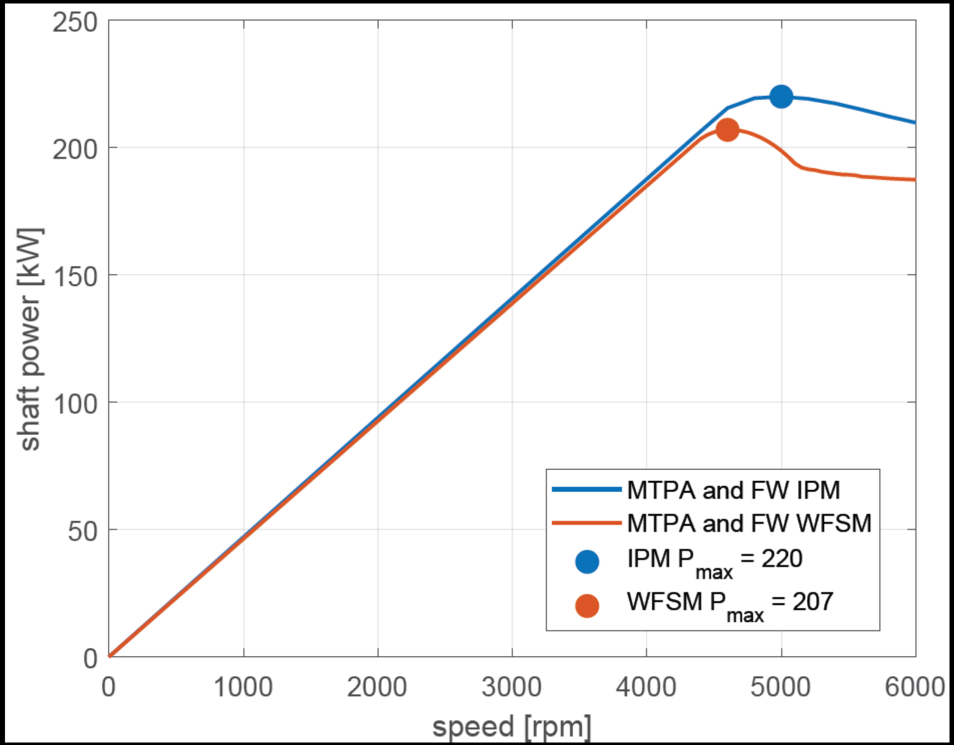
Mechanical and Thermal Design Optimisation

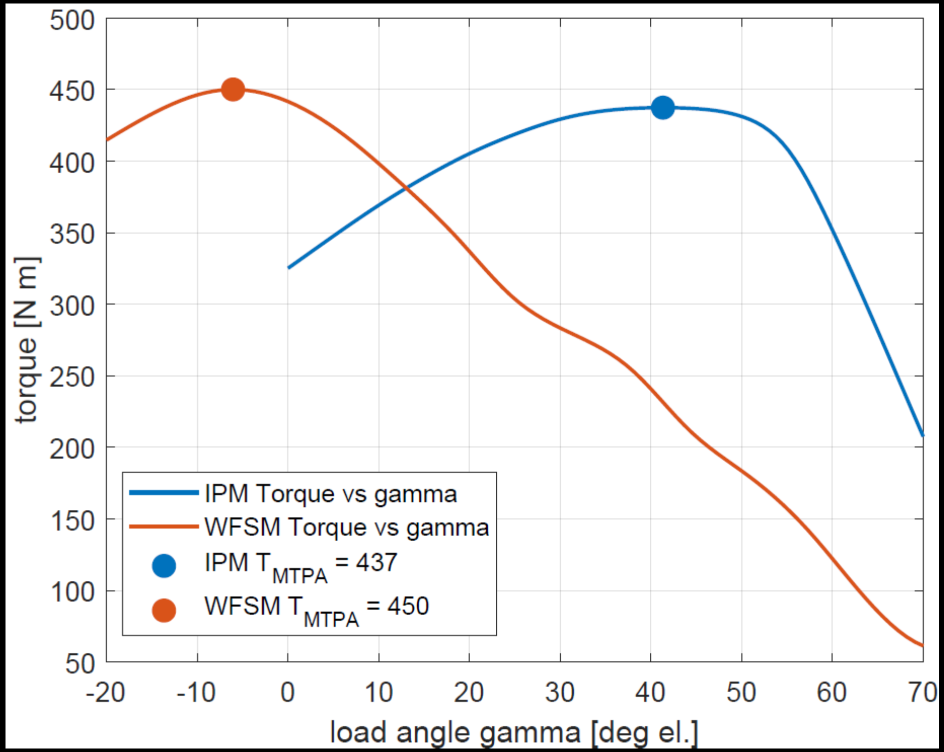




Performance comparison

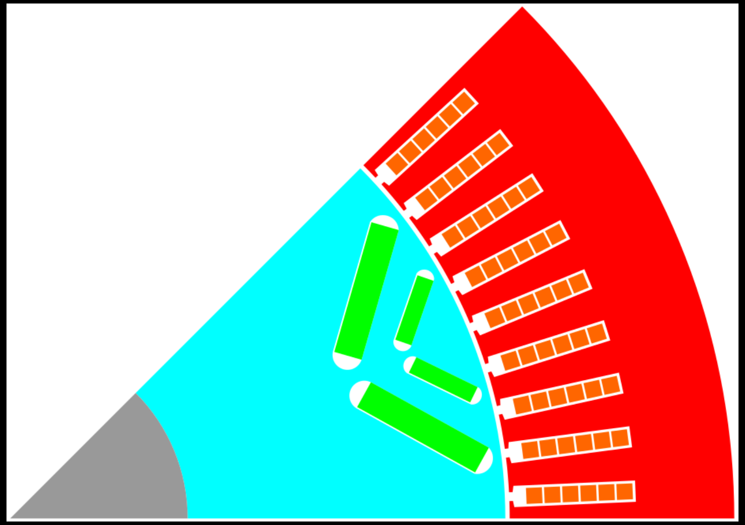
- The peak power is slightly higher for IPM compared to WFSM, since the base point is at higher speed, meaning that the IPM has lower flux linkage in this working point.
- The WFSM design with field winding shows a slightly higher peak torque compared to IPM

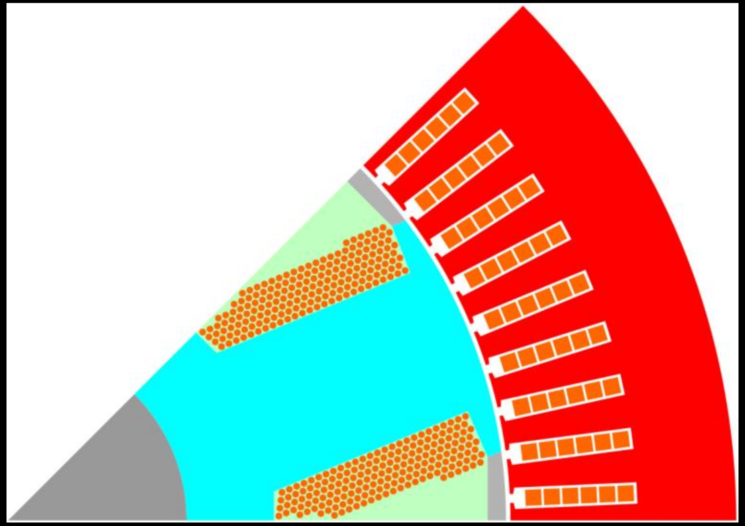




Traction Wound Field Machine – Case Study (2)

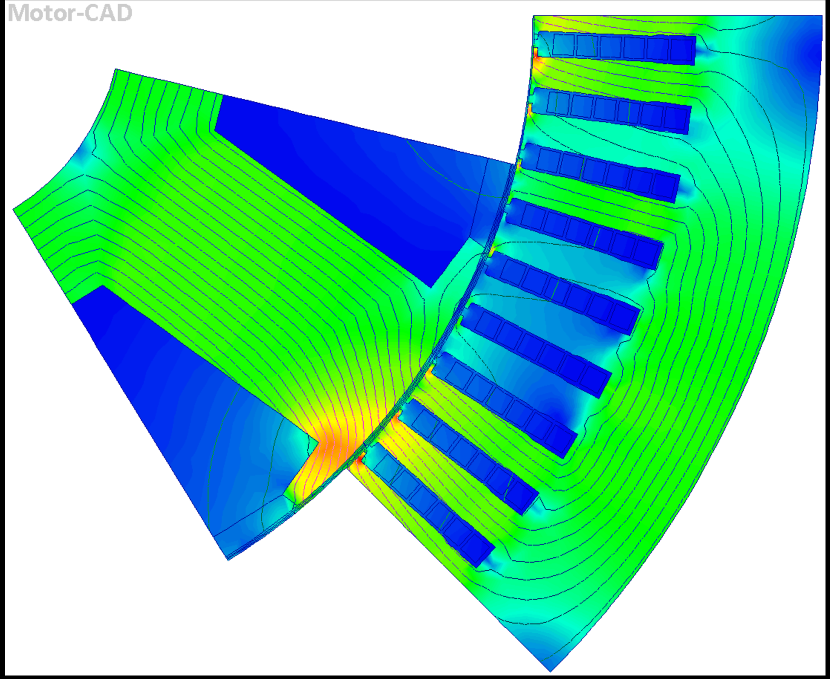
- Using as reference Chevy Bolt, IPM motor an equivalent WFSM machine is designed
- 72 slots, 8 poles
- Same stator as Bolt IPM
- Stator Water Jacket cooling
- Rotor shaft cooling

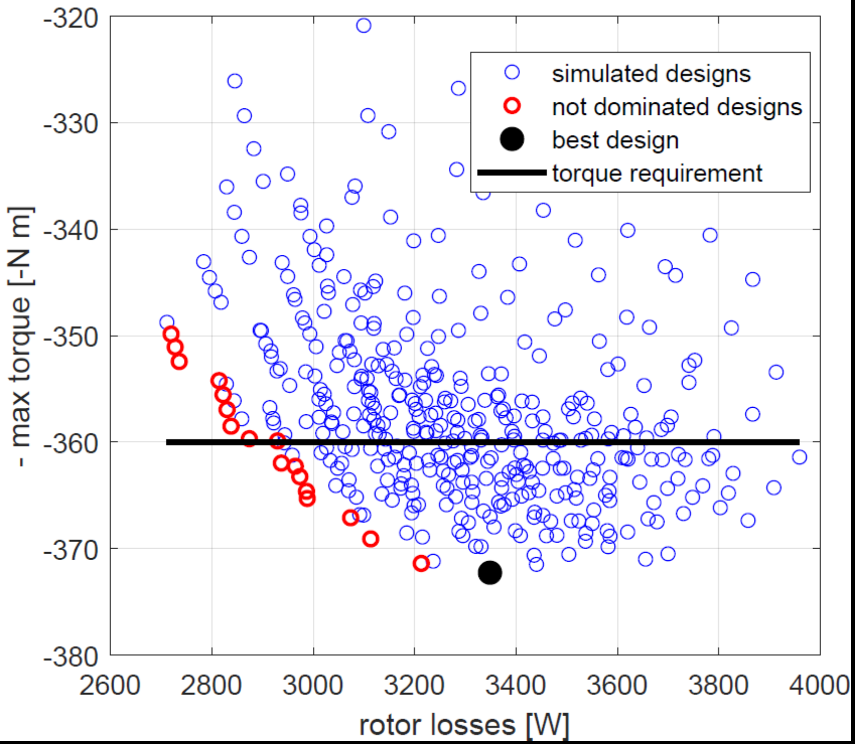




Traction Wound Field Machine – Case Study

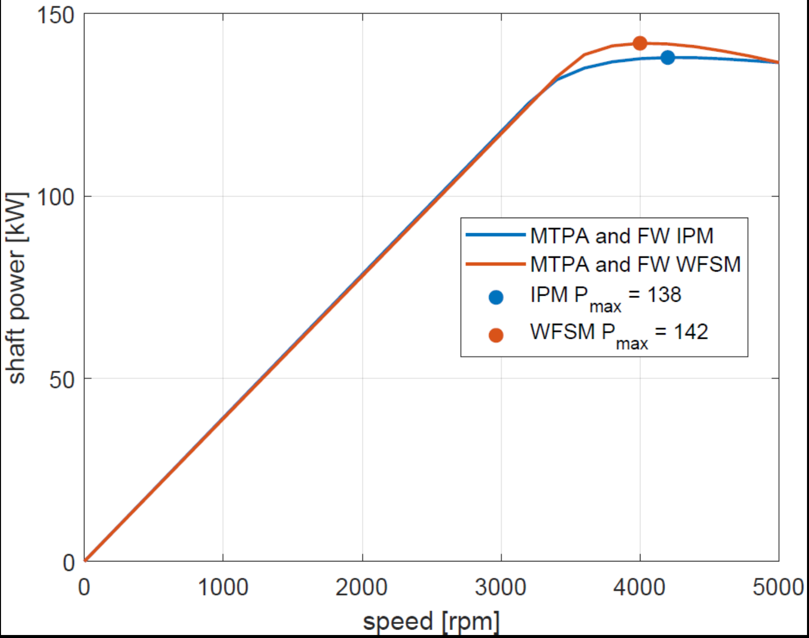
- Optimal rotor geometry
- Maximize average torque
- Minimise torque ripple
- Minimise weight
- Maximize efficiency
- Maximum Von Misses stress below Yield stress

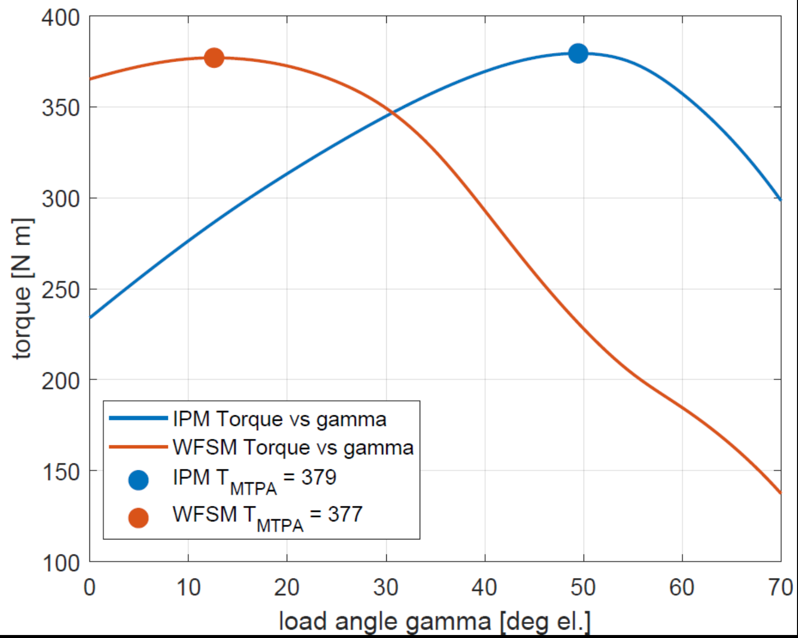




Traction Wound Field Machine – Case Study

- The peak power is slightly higher for IPM compared to WFSM, since the base point is at higher speed, meaning that the IPM has lower flux linkage in this working point.
- The WFSM design with field winding shows a slightly higher peak torque compared to IPM





Conclusions

- Rare earth free solutions for traction electrical machines represent a viable option:
  - Performance
  - Cost
  - Sustainable production
- Induction and Synchronous Machines performance require a detailed digital design process
- Multiphysics optimisation
- Innovative designs key to further developments
- Actual and future design trends:
  - Hairpin winding
  - Liquid cooling
  - Special electrical steel
  - Copper alloys (additive manufacturing)
  - Optimal lamination shapes

Acknowledgements

- This presentation is partly based on the joint research and collaboration: University of L’Aquila and Ansys MDL
- This work was partly supported by the European Union’s Horizon 2020 Research and Innovation Program through ReFreeDrive under Grant 770143.

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